SENSITIVITY OF 96 AND 120-HOUR NUMERICAL MODEL TROPICAL CYCLONE POSITION FORECASTS TO INITIAL POSITION ERRORS

THESIS

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Abstract

Global Forecast System (GFS) western Pacific tropical cyclone track forecasts from the 2011, 2012, and 2013 seasons (87 storms) were compared to Joint Typhoon Warning Center (JTWC) tropical cyclone best track data and warning bulletins in order to determine the sensitivity of 96 and 120-hour tropical cyclone position forecasts to initial position error. A tropical cyclone vortex tracker, which uses seven different model parameters to track storm centers, was implemented to determine model forecast positions. The differences between JTWC analysis positions and the model-derived vortex positions were analyzed at each forecast hour (00, 12, 24, 36, 48, 72, 96, and 120). The relationship between the geographical spread among the model vortex-tracking parameters and forecast errors was also considered. Correlations between error at each forecast hour and the initial 00-hour error suggest that position error has no effect on forecast error at 96 and 120-hours.

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First and foremost, I would like to thank my Lord and Savior Jesus Christ *who has graciously granted me the opportunities in this life. Secondly, to my beautiful wife, I am indebted to you for your tremendous support and love over these past six years.*

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SENSITIVITY OF 96 AND 120-HOUR NUMERICAL MODEL TROPICAL CYCLONE POSITION FORECASTS TO INITIAL POSITION ERRORS

I. Introduction

Tropical cyclones represent a unique forecasting challenge because of their large size and capacity to interact with the atmospheric environment around them. While they exist predominantly over the open ocean, the tools to identify and monitor tropical cyclones have become so sophisticated that nowhere in the world does a tropical cyclone develop unnoticed. Tropical cyclones pose a significant threat to lives and property when they make landfall. In 2012 alone, there were twenty-five tropical cyclones of greater than 34 knots intensity and four tropical cyclones that reached super typhoon intensity in the Western North Pacific Ocean basin (Joint Typhoon Warning Center 2012). A super typhoon is classified as having a maximum sustained 1-minute surface wind of at least 67m/s (130 knots / 150 mph). This is the equivalent to a strong category four or category five hurricane on the Saffir-Simpson scale used in the Atlantic/Eastern Pacific basin, or a category five severe tropical cyclone in the Australian basin.

All tropical cyclones have the potential to damage property and disrupt lives if they make landfall, which is why tropical cyclones are closely monitored by specialized tropical cyclone forecast agencies around the world. Between 1970 and 2010, there were a total of 637 tropical cyclones across the globe that made landfall (Weinkle et al. 2012). Many U.S. military assets are among the locations affected by land-falling tropical cyclones. The more lead time commanders can be given in the form of tropical cyclone forecasts, the greater the potential to save assets in harm's way. Within the U.S. military, the U.S. Pacific Command comprises approximately 330,000 personnel, 180 ships, and 2,500 aircraft (about 1/5 of the total U.S. military strength) (United States Pacific Command 2013). Keeping people safe and avoiding damage to equipment is a major concern of military leadership. Evacuating people and moving equipment out of the path of a tropical cyclone are expensive measures, but having to replace damaged or destroyed equipment or other assets can be equally or far more costly. Vacating an area and moving equipment unnecessarily is burdensome to commanders and to the soldiers, sailors, marines, airmen and their families who support the mission, which is where tropical cyclone forecasting plays a crucial role. Tropical cyclone forecasts need to be as accurate as possible in order to save lives and equipment. Commanders need accurate information when determining whether their assets are in danger and to set appropriate conditions of readiness as needed. The Joint Typhoon Warning Center (JTWC) coordinates with the Air Force's 17th Operational Weather Squadron (17th OWS) and the Navy's Fleet Weather Center San Diego (FWC-SD) to provide tropical cyclone forecasts for U.S. military operations in the Pacific Ocean. This project supports these weather centers by studying error statistics in tropical cyclone numerical weather prediction used at these and other forecast centers.

The mission of the 17th OWS, located at Joint Base Pearl Harbor-Hickam, is to provide accurate, timely, and relevant environmental situational awareness and mission tailored, operational and tactical-level meteorological, oceanographic, volcanic ash, and space environment products to Air Force, Navy, and Army Commanders (Air Force Weather Agency 2010). These commanders are spread across the 113 million square miles of the Pacific theater, operating at 121 Department of Defense (DoD) installations (Air Force Weather Agency 2010). Similarly, the mission of the Fleet Weather Center San Diego, located in San Diego, California, is to provide full-spectrum weather services to shore-based naval aviation, afloat naval units, naval installations, contingency exercises and operations in order to facilitate risk management, resource protection, and mission success of fleet, regional, and individual unit commanders (Fleet Numerical Meteorology and Oceanography Center 2010). JTWC, a joint Navy and Air Force command, provides tropical cyclone reconnaissance, forecasting, warning, and decision aids to provide support to United States government agencies operating in the Pacific and Indian Oceans (Air Force Weather Agency 2009).

Numerical weather prediction (NWP) models are a critical tool used by JTWC to forecast tropical cyclone position and intensity. Since the size of a typical tropical cyclone vortex is comparable to NWP resolution, their true intensity can only be captured by assimilating an artificial vortex into the model domain at the correct position and with the correct intensity when the model is initialized. Artificial tropical cyclone structure, position, intensity, and motion data is commonly referred to as a *bogus* among tropical cyclone forecasters. Bogus data does not come from actual meteorological observations, but rather the forecaster's interpretation of storm structure based on available observational data. By manipulating the initial vortex with bogus data, forecasters can improve the storm analysis in the model and potentially improve track and intensity forecasts. However, error in this artificially embedded vortex may grow throughout the model run, causing the model to misrepresent the true behavior of the tropical cyclone throughout the forecast hours.

The purpose of this project is to investigate the effect of 00-hour tropical cyclone positional errors on the 96 and 120-hour tropical cyclone track forecasts within the GFS model with a focus on the western North Pacific basin, defined by JTWC, as north of the equator, east of the Malay Peninsula (100 deg E) eastward to the International Date Line (180 deg W). By quantifying the model initialization error and tracking the propagation of that error forward in time, forecasters will gain insight into how the model responds to initial position error and how to evaluate a model's potential accuracy for short range and long range track forecasts. By better understanding model sensitivities, forecasters may improve tropical cyclone forecast accuracy, which can save money and lives by providing commanders a clear picture of severe weather impacts and how their personnel and assets could be affected.

II. Background

The tropical cyclone track forecasting skill of operational numerical weather prediction has steadily improved as modeling techniques and the models themselves have been upgraded. In the western North Pacific basin, the typical 96-hour model forecast error has decreased from 535 km in 2001 to 328 km in 2011. The 120-hour model forecast error has seen a similar decrease from 778 km in 2001 to 467 km in 2011. The average errors in 2011 for the 96 and 120-hour tropical cyclone forecasts are comparable to the average tropical cyclone forecast error from 1996 at 48 and 72-hours, respectively (Joint Typhoon Warning Center 2012). This steady increase in forecast accuracy can be attributed to a number of factors, including more accurate models, increased forecaster experience, and more frequent and reliable storm observations. With respect to tropical cyclone observations, the Pacific basin is very different from the Atlantic basin in that in-situ aircraft observations, primarily via Air Force WC-130 and National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft, have been nearly non-existent since the late 1980s (Guard et al. 1992). WC-130 aircraft still observes hurricanes in the Atlantic basin and eastern North Pacific basin in support of the National Hurricane Center (NHC). Figure 1 illustrates the increase in the dependence on satellite observations for tropical cyclone forecasting in the western North Pacific between 1971 and 1992, as well as the decline in aircraft observations over the same period.

Tropical cyclone forecast position errors vary from storm to storm and from basin to basin. Pike and Neumann (1987) analyzed the average positional error for storms in each of the six major ocean basins and developed an objective method to combine the difficulty of forecasting tropical cyclone position in each basin. They concluded the mean storm latitude was a strong predictor of basin forecast difficulty. Basins where the mean storm latitude was greater than 20 deg from the

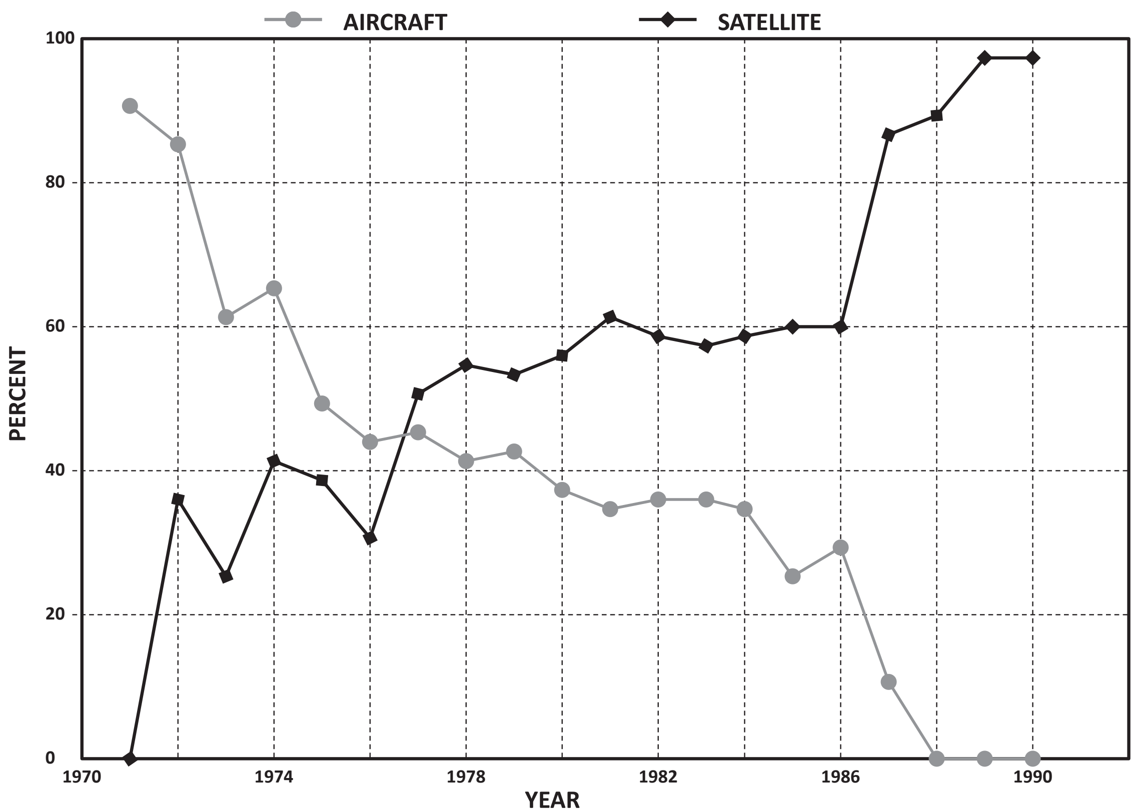

Figure 1. Trend in the percentage of tropical cyclone warnings in the western North Pacific based primarily on satellite and aircraft reconnaissance from 1971 to 1990. Ocean buoys and radar are among the other observations intermittently used by forecasters to aid in tropical cyclone forecasting. Adapted from Guard, Carr, Wells, Jeffries, Gural, and Edson (1992).

equator had, on average, larger forecast position error at all forecast periods. Both the North Atlantic and the western North Pacific basins, according to Pike and Neumann, had mean storm latitudes greater than 20 deg N. Pike and Neumann concluded that the North Atlantic and western North Pacific basins ranked as the second and third, out of six, most difficult basins for tropical cyclone track forecasting due to the mean latitude of storms in these basins. Forecasting difficulties in the western North Pacific are particularly concerning to JTWC given the large concentration of DoD assets in that basin.

The average tropical cyclone forecast position error for the 2012 tropical cyclone season was 300.9 km at 96-hours and 414.8 km at 120-hours for storms in the western North Pacific analyzed and forecast by JTWC (Joint Typhoon Warning Center 2012). Forecasters use multiple tools to forecast tropical cyclone positions. Chief among these tools are deterministic NWP models and ensembles of models. Models are forecasting tools, which take an initial state of the atmosphere and predict how those conditions are expected to change with time. NWP models are comprised of mathematical equations that represent the behavior of a physical atmospheric system. An ensemble of models is a collection of several deterministic numerical weather prediction models with slightly altered initial conditions and/or model physics. The agreement or non-agreement among the ensemble members is quantified via the ensemble spread, or range of possible outcomes.

2.1 Models

This study analyzes the performance of the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), one of the global forecast models used by JTWC and the 17th OWS, was the global deterministic model chosen for this study. The GFS model is a dynamical global spectral model that uses spherical harmonics to solve the physical equations of motion yielding solutions for tropical cyclone position and intensity. JTWC also employs other global and regional deterministic models, as well as statistical models, for track and intensity forecasting. Statistical models do not explicitly consider the physics of the atmosphere but rather apply empirical relationships between storm intensity, storm location, and time of year to predict tropical cyclone position and intensity.

NCEP developed the Global Forecast System model in 1981. The model is run four times per day (00, 06, 12, and 18 UTC) with output in 6-hour time steps out to 384 hours. The GFS model spectral resolution is currently wave number 574 (roughly equivalent to 25 km horizontal grid spacing) with 64 vertical levels

(University Corporation for Atmospheric Research 2010). This resolution is sustained through the first 192 hours of the forecast, thereafter reducing to wave number 190 (roughly equal to 80 km horizontal grid spacing) with 64 vertical levels out to 384 hours. The version of the GFS model used in this study outputs model data to a $0.5° \times 0.5°$ grid.

2.2 Bogusing

As discussed earlier, *bogusing* is the process of influencing the model analysis around the tropical cyclone using synthetic tropical cyclone observations. The purpose of this process is to improve both the model analyses and forecasts, and consequently, to improve the forecast guidance provided by JTWC and other forecast centers to their customers. The three standard methods for inserting bogus tropical cyclone observations into a numerical model are modifying the background, adding synthetic observations, and replacing the vortex.

The first bogusing method, modifying the background field, is applied in NCEP's GFS model. This method involves relocating the forecasted vortex position from the previous model run to the current JTWC bogus position prior to data assimilation. By relocating the background tropical cyclone, the disparity between the background and real-time observations is decreased, improving the assimilation of existing observations (Peng et al. 1993).

The second bogusing method, which is used by the Japanese Meteorological Agency's Global Spectral Model (JGSM) and the Navy's Global Environmental Model (NAVGEM), involves adding synthetic observations to the data assimilation field. Tropical cyclone analyses can be improved by adding artificial observations before the objective analysis is performed. However, the intensity of the storm generated in this fashion is usually weaker than the actual cyclone intensity (Peng et al. 1993).

The final and most complex bogusing method, employed by the Geophysical Fluid Dynamics Laboratory Navy (GFDN) model, is vortex replacement (Peng et al. 1993). This scheme replaces the model's tropical cyclone vortex analysis with an externally-generated tropical cyclone vortex. The artificial vortex is still generated within the GFDN model, although it is accomplished in a separate simulation which is heavily influenced by JTWC bogus data.

2.3 Best Tracks

The Joint Typhoon Warning Center maintains an archive of tropical cyclone track data, also referred to as *best track* data, for all storms within its area of responsibility (AOR). The best track data contain 6-hourly tropical cyclone positions and intensities that are quality-controlled well after each tropical cyclone has dissipated and finalized after each tropical cyclone season has ended. The post-analyzed best track positions can differ from the *working best track* position in the tropical cyclone warnings by 200 km or more. There is often a larger amount of raw data available for post-storm analysis, more analysis time, and a complete storm history available to produce storm best tracks for the JTWC archive (Chu et al. 2002). JTWC has archived best tracks dating back to 1945, but best tracks prior to the 1985 season should be handled with caution due to the lack of supporting documentation available for those storms (Chu et al. 2002). In addition to position and intensity, archived JTWC best track data since 1998 also include the minimum sea level pressure and the level of tropical cyclone development.

III. Methodology

3.1 Data Employed

For this study, 87 western North Pacific tropical cyclones dating from 1 January 2011 to 31 December 2013 were analyzed. To begin, post-analyzed best track data from the 2011 (27 storms) and 2012 (27 storms) seasons were downloaded from JTWC's public website. Because post-analyzed best track data are not yet available for the 2013 tropical cyclone season (33 storms), JTWC real-time warning bulletins[1] were downloaded and used. GFS model data were obtained for dates and times correlating with the storms of each season. The GFS model data were obtained from the NOAA Operational Model Archive and Distribution System (NOMADS) archive website (*http://nomads.ncdc.noaa.gov/data*). For all model runs (00, 06, 12, and 18UTC) and for each forecast hour between 00 (analysis) and 120 hours at 6-hour intervals.

3.2 Best-Track Data Extraction and GFS Matching

An original Matrix Laboratory (MATLAB®) software routine performed numerical computations using JTWC best track data, JTWC warning bulletins, and GFS output and generated output figures for this project. The MATLAB® algorithm was created to load and read through JTWC warning bulletins and best track data as well as record the tropical cyclone position (latitude/longitude) and intensity (both MSLP and sustained wind) at six-hour intervals throughout the lifetime of each storm.

The algorithm searched for the GFS model run corresponding to the best-track data entry. Some GFS model run files were not available or contained corrupted

[1] Real-time warning bulletins can be less accurate than the post-analyzed best track data, however in order to analyze the 2013 season, warning bulletins were the only available option for this study.

data and thus could not be used as part of this study. However, if the file was available, latitude and longitude grids, mean sea level pressure (MSLP), and 850 and 700mb u and v wind components and geopotential height fields, were extracted. These parameters were used to locate the tropical cyclone vortex within the GFS model field as described in Marchok (2002).

3.3 GFS Vortex Location Algorithm

In NCEP's vortex tracker, a Barnes Analysis algorithm is employed to refine the location of the vortex of each parameter field. The algorithm, which iteratively refines the model grid resolution, is computationally expensive but does not alter the location of a local maximum or minimum value within the model parameter field. The algorithm interpolates the model parameter field to a finer resolution using a weighting function and the model parameter values at the model's original grid resolution, but regardless of the ultimate grid resolution, the vortex position is still fount at the local maximum (or minimum depending on the parameter) in the model parameter field. Since the locations of these maxima (or minima) remain unchanged, even with finer model resolution, the full Barnes Analysis algorithm was not used to find the vortex within the model fields for this study.

As noted previously, the winds within each model are output to the user in component (zonal, u, and meridional, v) form. The wind components at both 850 and 700mb were evaluated using equation 1 below to find the wind speed magnitude at both levels.

$$V = \sqrt{u^2 + v^2} \tag{1}$$

To determine the relative vorticity at 850 and 700mb to locate the vortex within the GFS model field, the zonal derivative of the v component of the wind field and the meridional derivative of u component of the wind field were first calculated. In order to accomplish these derivatives, the centered difference method was used on all interior grid points of the model:

$$\frac{du}{dx} = \frac{(u_{x+dx}) - (u_{x-dx})}{2dx} \tag{2}$$

$$\frac{dv}{dy} = \frac{(v_{y+dy}) - (v_{y-dy})}{2dy} \tag{3}$$

After computing the zonal and meridional derivatives on the two wind components, equation 4 was applied to calculate the relative vorticity at each interior model grid point for both the 850 and 700mb pressure levels:

$$\zeta = \frac{dv}{dx} - \frac{du}{dy} \tag{4}$$

The full Barnes Analysis algorithm is applied operationally to the GFS model. In an effort to closely follow operational standards, a modified Barnes Analysis was used for this study. The modified tropical cyclone vortex tracker used in this study employs the same seven parameters to locate the position of the vortex as the original NCEP tropical cyclone tracker (Marchok 2002). For each of the seven parameters analyzed, an area of 5 model grid points or 2.5° in each direction from the best-track or warning location was analyzed in order to find the minimum/maximum (depending on the parameter) grid point within the parameter field. The 2.5° restriction helped ensure that the vortex itself was located and not an extraneous maximum or minimum along the outer periphery of the storm. Each of the following parameter fields was analyzed separately to determine a vortex position for the forecast.

The first parameter used to locate the tropical cyclone vortex was the minimum mean sea level pressure (MSLP). The minimum pressure value and location within 2.5° (5 model grid points) of the JTWC best-track were determined. If there were multiple grid points with the same minimum pressure value, the grid point closest to JTWC's reported center point was used.

The next parameter analyzed was the relative vorticity at 850mb. The relative vorticity field was not inherently calculated by the GFS model, but rather was derived from the u and v components of the wind according to equations (2) through (4). At 850mb, the vortex position was defined as a maximum in the relative vorticity field. As with the MSLP and all other parameters, if there were multiple grid points yielding the same maximum value, the grid point nearest the location in the JTWC best-track was used.

Relative vorticity at 700mb was the next parameter analyzed. It was computed in the same manner as the relative vorticity at 850mb. At 700mb, the vortex of a tropical cyclone is still rotating cyclonically and thus the maximum in the 700mb relative vorticity field was used to locate the vortex.

The next parameter analyzed was the geopotential height field at 850mb. Due to the cyclonic flow in the lower levels of a tropical cyclone, the minimum in the geopotential height field at 850mb was used to locate the vortex center. The geopotential height is inherently calculated in the model and thus did not need to be altered. The minimum in the height field around the reported JTWC best-track position was found in the same fashion as the previous three parameters.

The fifth parameter analyzed was the geopotential height field at 700mb. Much like the geopotential height field at 850mb, the height field at 700mb is dominated by the cyclonic flow in the lower levels of the tropical cyclone and as a result, the minimum in the height field was again used to locate the vortex from this parameter.

At this point, the geographical mean of the five individual parameter vortex locations was determined. This is not the final vortex location, but rather an intermediate location used to analyze the wind field at both 850 and 700mb. Since the wind field at both levels generally has weak winds near the tropical cyclone center (or eye) as well as weak winds along the periphery of the storm, the $2.5° \times 2.5°$ search box for the wind minima at both levels was centered on this intermediate vortex location in order to help minimize the potential of finding weak winds along the periphery of the storm rather than the weak winds associated with the tropical cyclone center. The wind magnitude computed using (1) was analyzed to find the storm-center wind minimum at both levels.

Once all parameter fields had been analyzed, the average latitude and longitude of the seven individual vortex fixes defined the estimated location of the vortex for the GFS model run. The distance of each individual parameter vortex fix from the overall vortex position fix was computed. The standard deviation of these distances was computed and recorded as the parameter spread for each GFS model run.

3.4 Computing GFS Forecast Position Errors

The true location (latitude and longitude) of the storm in each of JTWC's best track files and warning bulletins were compared to the model derived vortex location at the corresponding date and time in order to calculate the positional error present at each forecast hour of each forecast. The position error between JTWC's best-track (or warning bulletin) position and the located model vortex position was the distance between the two positions. Once this error had been calculated and recorded, it was decomposed into two components, along-track (ATE) error and cross-track error (XTE). Figure 2 depicts these components. Along-track error can be thought of as error in forecasting the speed of the storm, while cross-track error can be though of as error forecasting the direction of the storm.

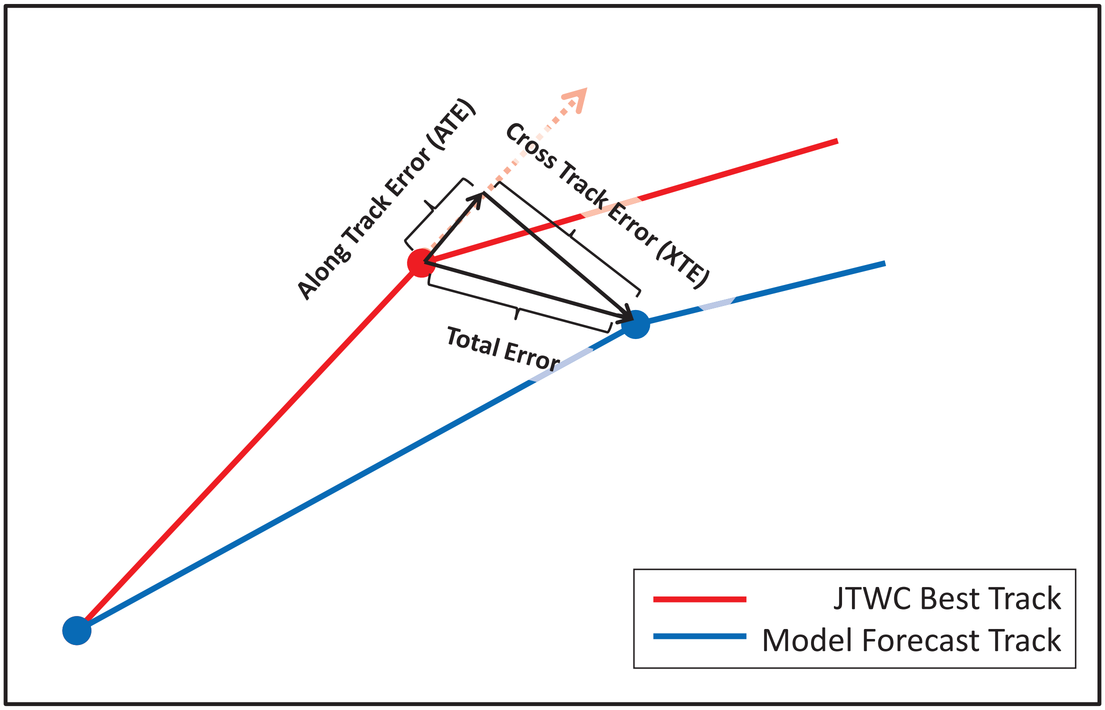

Figure 2. Depiction of along and cross-track errors. This figure shows how both along-track error and cross-track error relate to total error. The red line shows the track of the tropical cyclone according to the JTWC best-track while the blue line represents the storm track according to the GFS model. The red dotted line shows the motion vector of the storm.

Additional data was saved for each GFS run, including date and time of best-track analysis, the forecast hour (00 - 120), the best-track latitude and longitude at GFS run time, the best-track maximum 1-minute sustained wind, the best-track minimum MSLP and the spread among the seven model parameters used in locating the model vortex.

To visually verify that the algorithm accurately located the model vortex and continued to track the same vortex throughout the life cycle of the storm, two plots were generated. The first depicted the track of the tropical cyclone along with each of JTWC's forecast bulletin forecasts. The second plot depicted the best-track of the tropical cyclone along with the tropical cyclone vortex forecast positions determined

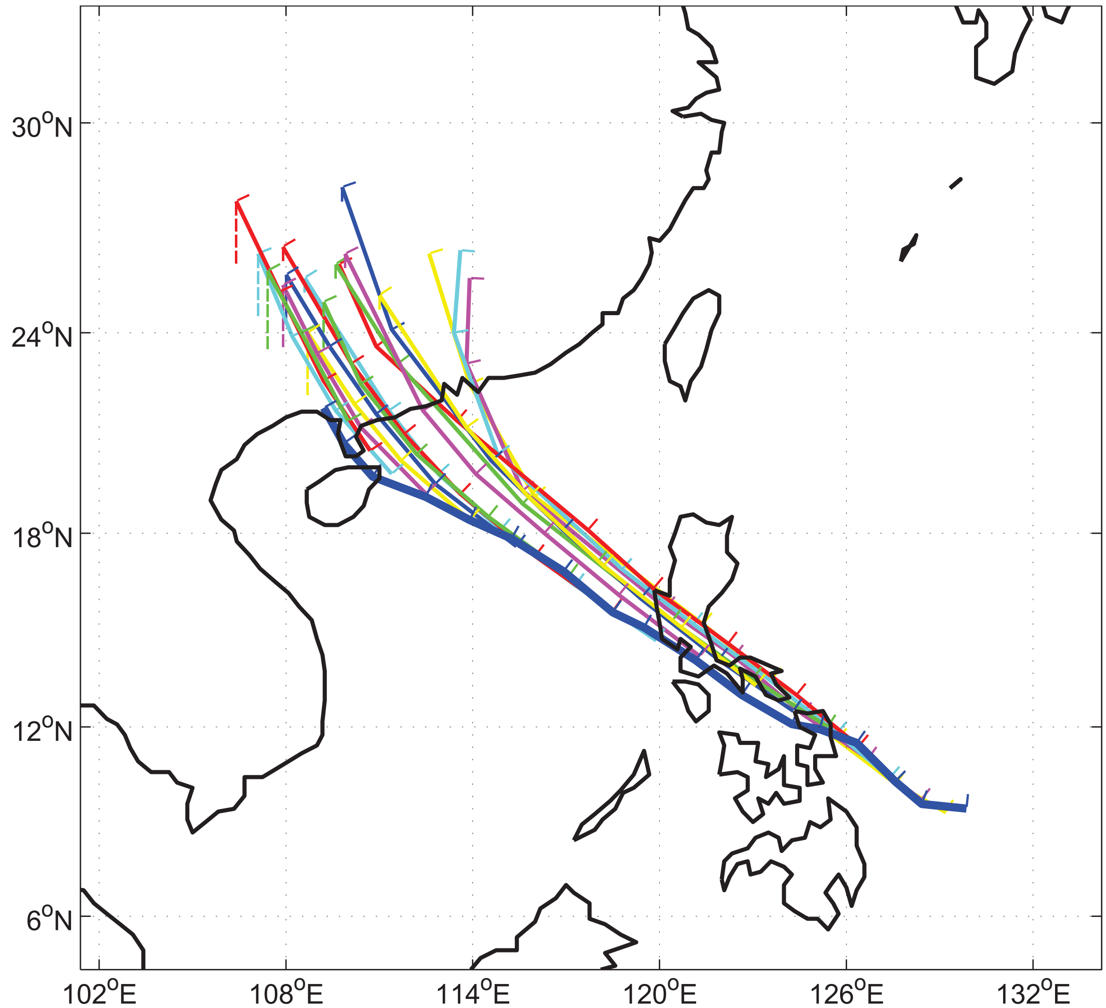

Figure 3. GFS Model analysis for 2013 tropical cyclone 06W. The GFS model vortex located using the MATLAB® algorithm structure described above. The bold blue line shows the storm track from GFS analyses while the thinner, colored lines show each of JTWC's forecasted trajectories for the same storm. The small tick marks along both the bold trajectory line as well as each of the forecast lines indicate a unique forecast time.

from the GFS model. An example of these plots are shown in Figures 3 and 4.

After quality-controlling the vortex trackers, the forecast position errors for each storm were compared with a number of parameters in an effort to find correlations. Figures depicting these correlations were created, a subset of which are evaluated in the following chapter. The data from each individual storm were combined with all other analyzed storms from each season in order to analyze the dataset as a whole

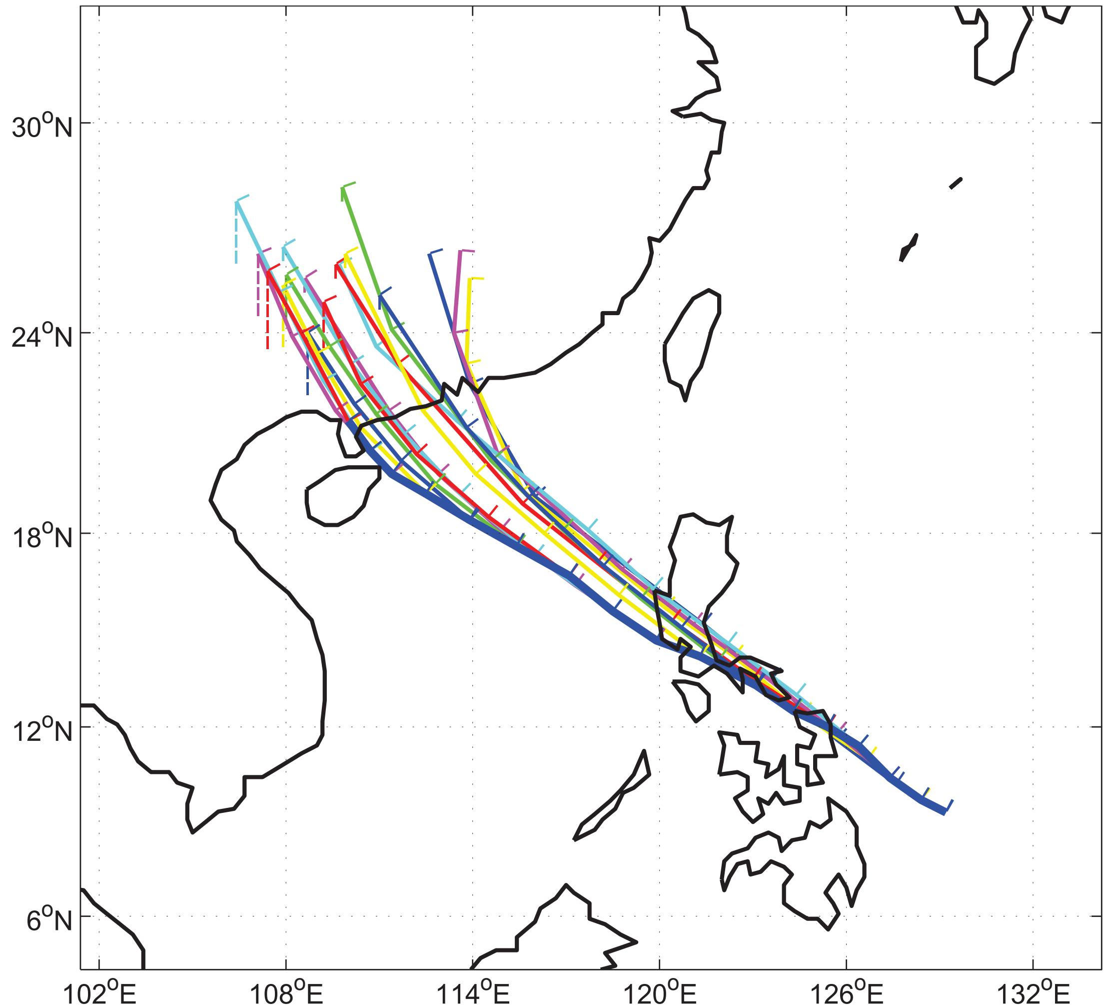

Figure 4. JTWC best track trajectory of 2013 tropical cyclone 06W. The bold blue line shows the storm track while the thinner, colored lines show each of JTWC's forecasted trajectories for the same storm. The small tick marks along both the bold trajectory line as well as each of the forecast lines indicate a unique forecast time.

and offer a comprehensive conclusion. Each storm season was first analyzed individually in order to attain individual season statistics then seasons 2011 and 2012[2] were analyzed together to give a more comprehensive look at the GFS model errors.

The scatter-plots include best fit lines, correlation coefficients, and sample size. The intrinsic MATLAB® function *lsline* was used to draw the least-square best fit

[2]The 2013 season was not initially included in the multi-season analysis because warning bulletins were used in the analysis rather than post-analyzed best track data.

line. The correlation coefficient was calculated using the function *corrcoef*, intrinsic to MATLAB®, which calculates the correlation coefficient, r, following equation (5) in which $C(i{,}j)$ is the covariance, following equation (6).

$$r(i{,}j) = \frac{C(i{,}j)}{\sqrt{C(i{,}i)C(j{,}j)}} \tag{5}$$

$$C(i{,}j) = \sum_{k=1}^{N} \frac{(i_k - \bar{i})(j_k - \bar{j})}{N} \tag{6}$$

The correlation coefficient, r, is a measure of the strength and direction of the linear dependence between two variables. The result is a value between +1 and -1, inclusive, where +1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation (Rodgers and Nicewander 1988).

IV. Results

4.1 Overview

The principle objective of this project was to investigate the effect of 00-hour tropical cyclone positional errors on the 96 and 120-hour tropical cyclone track forecasts. The initial hypothesis to be tested was that a smaller 00-hour, or initial, tropical cyclone position error would yield smaller 96 and 120-hour positional forecast errors. In other words, any positional error introduced into the model during the model initialization would persist and grow throughout all subsequent forecast hours. Several different analyses were conducted of positional forecast error at every forecast hour and how these errors relate to a number of other storm attributes. These other attributes include the latitude of the storm, the minimum pressure at the storm vortex, the maximum sustained wind associated with the storm, the spread in the seven model parameters used in locating the model vortex, and the initial (00-hour) error for each forecast. In this analysis, storms stratified by intensity in order to examine whether better error statistics are attained when looking only at storms of a certain intensity. The 2013 storm season was analyzed in the same fashion as the 2011-2012 storm seasons in order to compare the results of using the JTWC warning bulletins versus using the post-analyzed best track data.

4.2 Forecast Error vs Initial Error

The first area studied was how the positional errors at each forecast hour relate to the initial positional error for each GFS model run. The correlation analysis shows a positive correlation between positional errors at forecast hours 12 and 24 and corresponding 00-hour positional errors (Figures 5 and 6). At forecast hours beyond 24 hours (36, 48, 72, 96, and 120), there is effectively no correlation between the GFS forecast position error and the 00-hour positional error (see Figures 7 through 11). This result shows that initializing the vortex within the model as accurately as possible will only affect the outcome of positional forecasts out to 24 hours. At forecast lengths of 36 hours and beyond, the primary driver of positional forecast error does not appear to lie in the accuracy of the initial bogus.

The following sections describe the correlations between initial (00-hour) forecast positional error and the forecast positional errors at each forecast hour (12 through 120). Figures 5 through 11, show scatter plots of initial (00-hour) error versus hourly forecast error with associated best fit line. Also provided with each plot are the sample size of forecasts and the correlation coefficient. The errors displayed in the figures are calculated and displayed in kilometers. The figures in this section depict GFS model errors calculated from the 2011 and 2012 storm seasons only.[1] For each plot, only the forecasts with a corresponding 00-hour forecast analysis were plotted. As mentioned earlier, some of the model runs were not available or corrupted and thus could not be analyzed as a part of this study.

4.2.1 12-hour Positional Error

The 12-hour positional GFS forecast error and the 00-hour positional forecast error were positively correlated with a correlation coefficient of 0.44 (Figure 5). The number of 12-hour forecasts with a corresponding 00-hour forecast was 1332. This positive correlation illustrates that a smaller 00-hour error (i.e. a more accurate bogus) will generally lead to a more accurate 12-hour position forecast.

[1] 2013 season data were not aggregated with the 2011 and 2012 storm seasons data because warning bulletins were used to determine analysis positions rather than post-analyzed best track data.

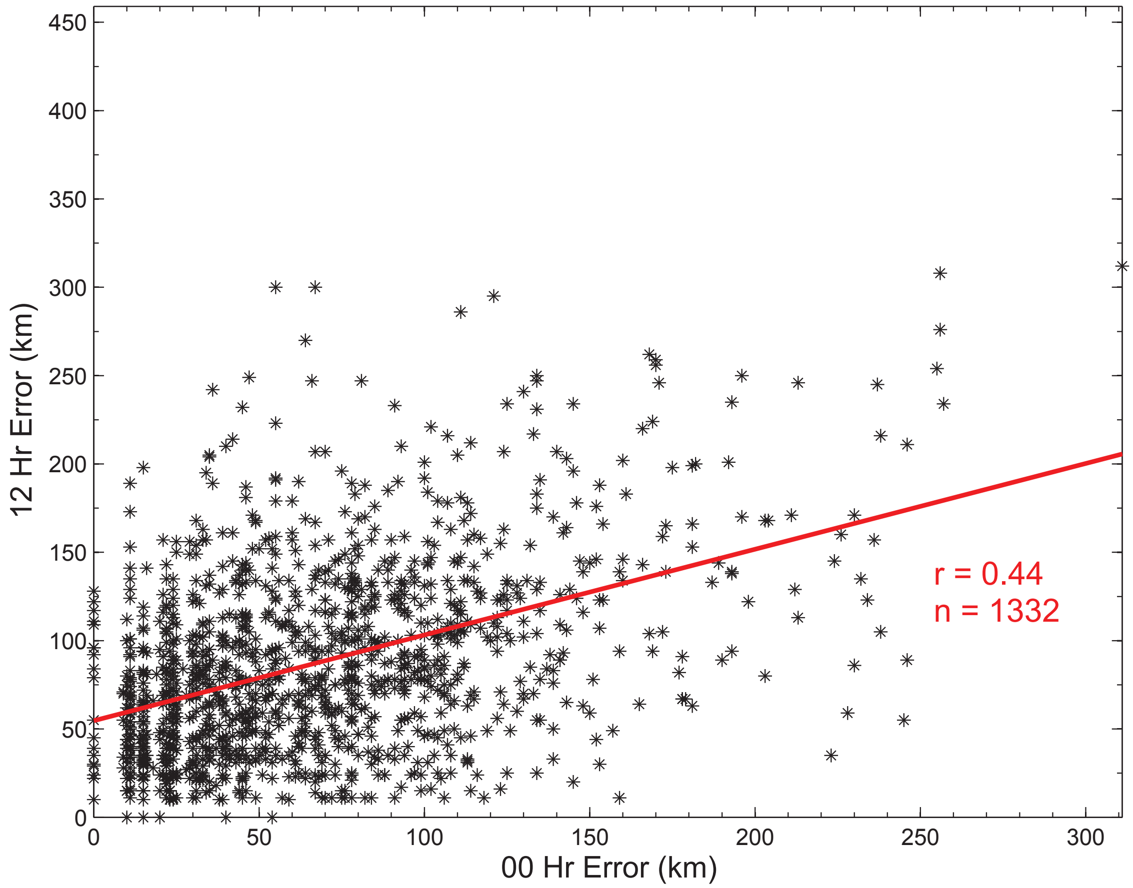

Figure 5. 12-hour forecast error vs 00-hour error. Scatter-plot of the 12-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

4.2.2 24-hour Positional Error

Similar to the 12-hour positional error, the 24-hour positional forecast error a positive correlation coefficient of 0.24 with 00-hour error for 1233 forecasts (Figure 6). This correlation suggests, as with the 12-hour error, that a smaller initial error will yield a smaller 24-hour positional error.

4.2.3 36-hour Positional Error

The correlation between the GFS 36-hour forecast positional error and the 00-hour positional error, yield a correlation coefficient of 0.18 (Figure 7). The

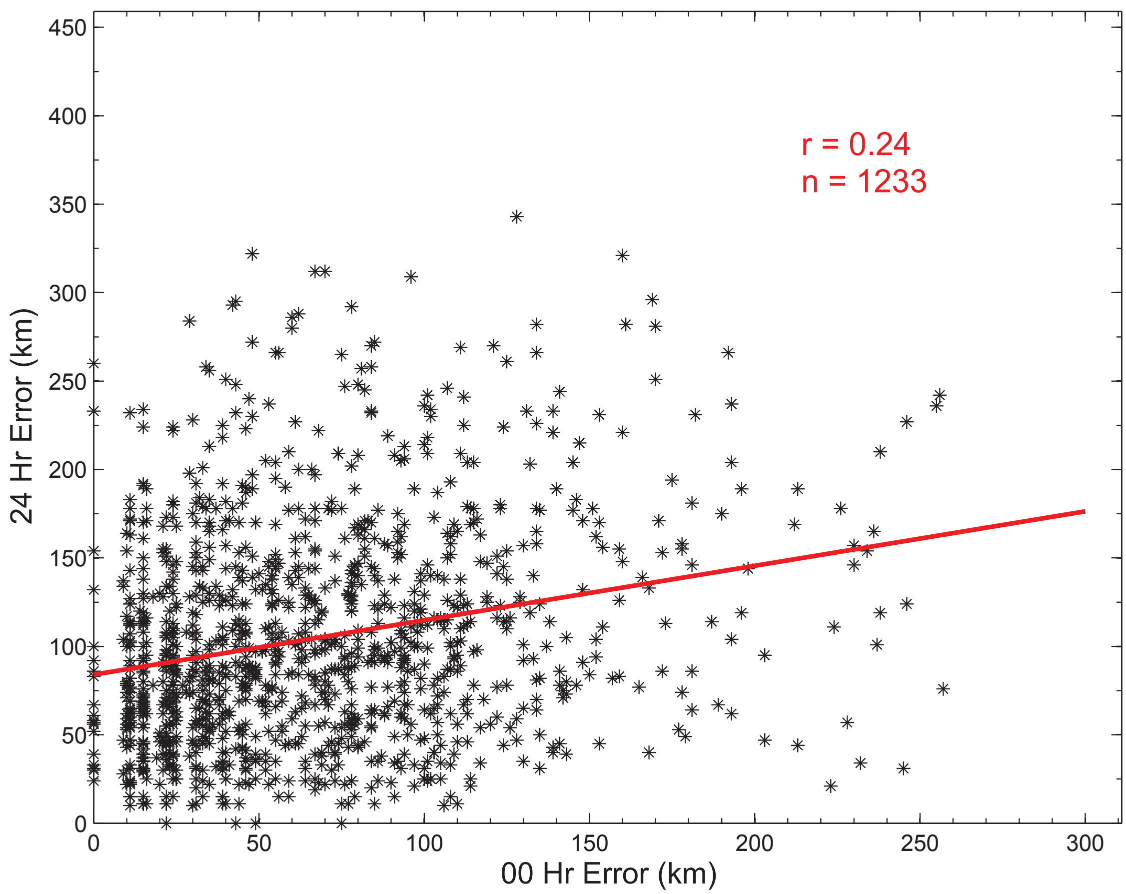

Figure 6. 24-hour forecast error vs 00-hour error. Scatter-plot of the 24-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

sample size for the this analysis was 1136 cases. It appears that by the 36-hour point, the relationship between vortex 00-hour positional error and forecast error becomes nearly insignificant.

4.2.4 48-hour Positional Error

Results for the 48-hour GFS forecast positional error versus 00-hour positional error analysis (Figure 8) are very similar to that of the 36-hour forecast results. The correlation coefficient was 0.10 for 1042 forecasts. Again the correlation between 00-hour error and positional forecast error though positive, was weak.

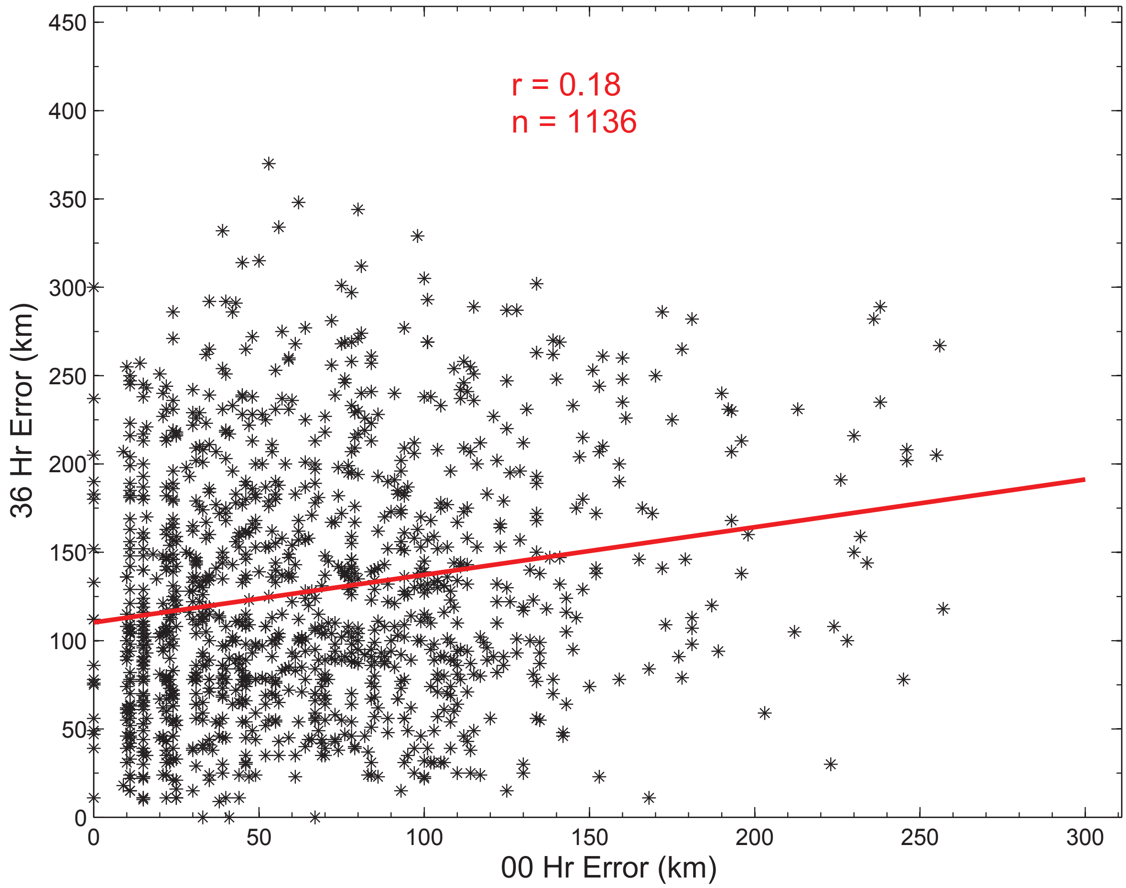

Figure 7. 36-hour forecast error vs 00-hour error. Scatter-plot of the 36-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

4.2.5 72-hour Positional Error

The analysis of 72-hour GFS forecast positional error versus 00-hour positional error revealed effectively no correlation between the two (Figure 9), with a correlation coefficient of 0.01 for a sample size of 855. The almost non-existent correlation between the positional forecast error and the 00-hour error depicted in this plot persists throughout the remaining forecast hours.

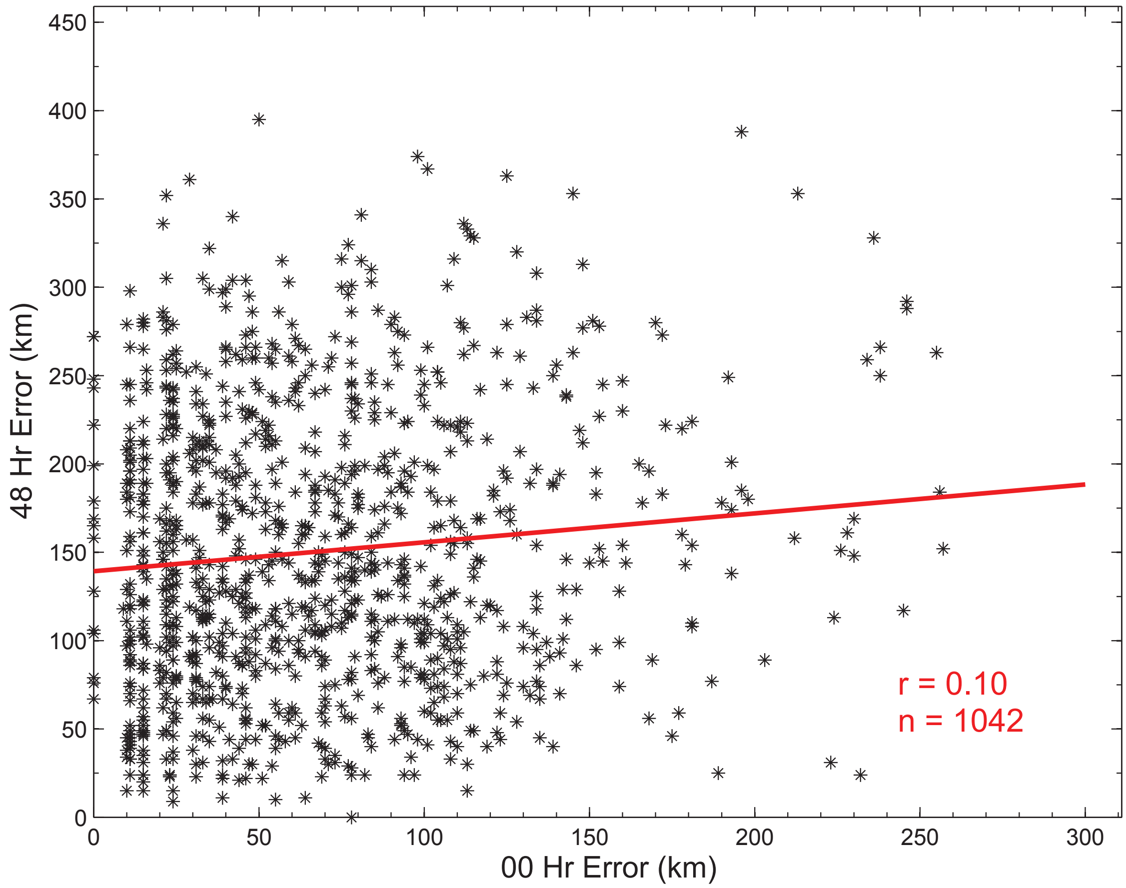

Figure 8. 48-hour forecast error vs 00-hour error. Scatter-plot of the 48-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

4.2.6 96-hour Positional Error

By 96-hours, a slightly negative correlation exists between the 00-hour positional error and the GFS forecast positional error, as seen in Figure 10. At 96 hours, the correlation coefficient has decreased to -0.06 for a sample size of 680. Interestingly the negative correlation suggests that, on average, degrading the initial vortex positional error actually corresponded with a slight improvement in the 96-hour forecast position.

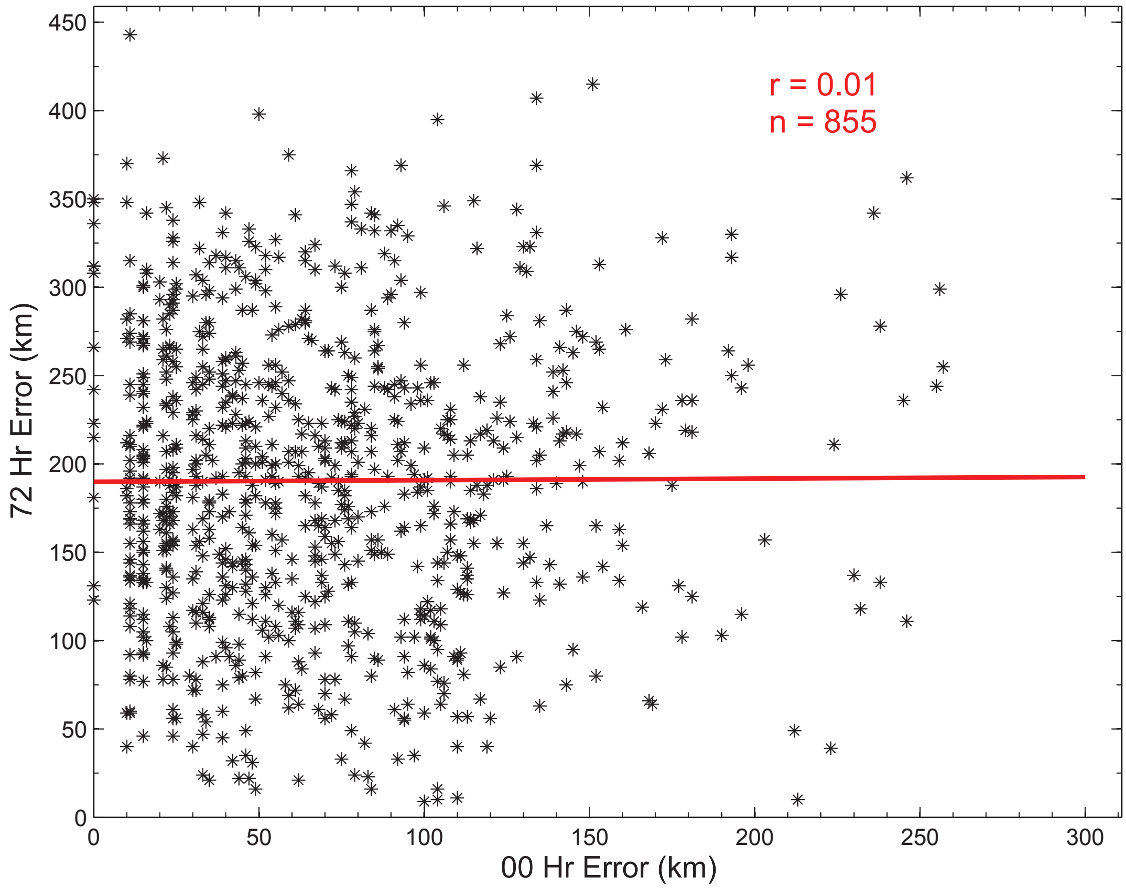

Figure 9. 72-hour forecast error vs 00-hour error. Scatter-plot of the 72-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

4.2.7 120-hour Positional Error

The analysis of 120-hour GFS forecast positional error versus 00-hour positional error, as for the 96-hour forecasts, revealed a slightly negative correlation (Figure 11). The correlation coefficient is -0.07 for a sample size of 502 forecasts. Again, this weak negative correlation implies that the 120-hour forecast was more accurate, on average, when the corresponding 00-hour forecast error was larger. However, given the small correlation values and complexity of potential forecast error sources, a causal relationship between the 00-hour position and 120-hour forecast cannot be said to directly cause the improvement.

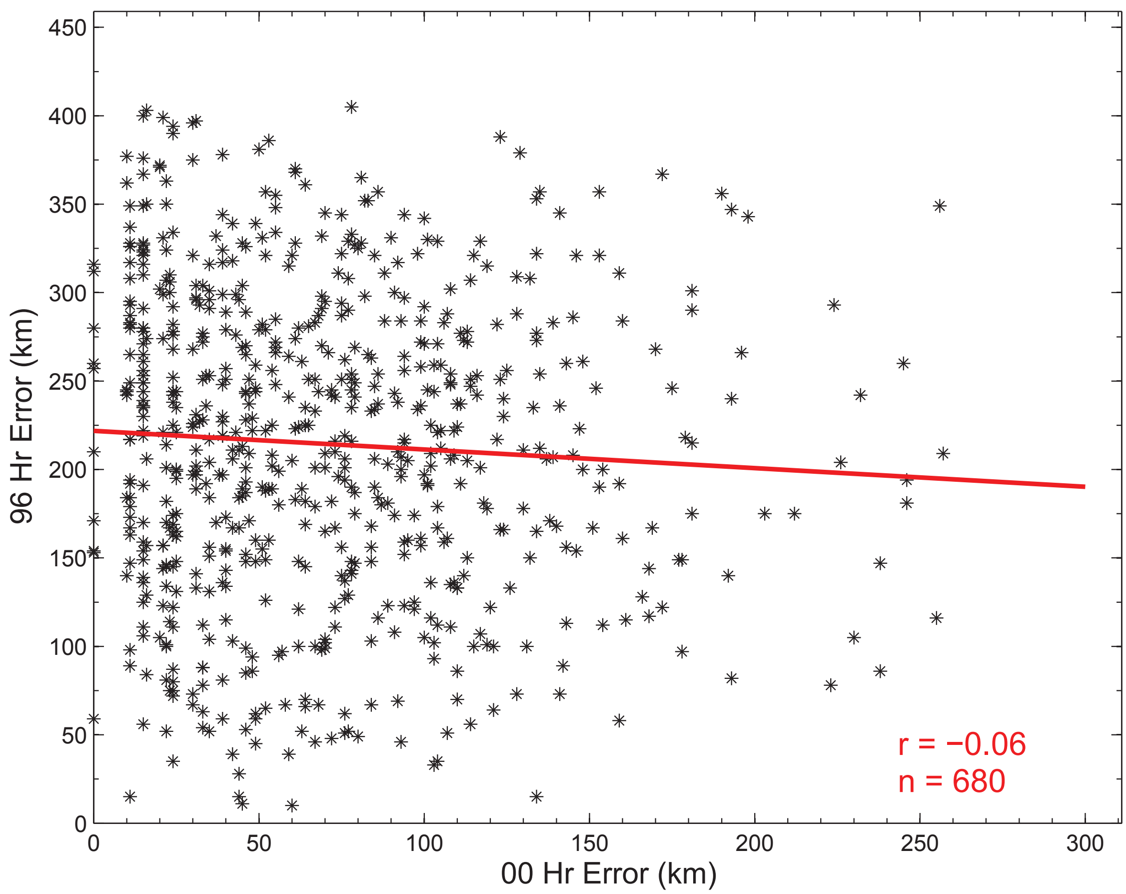

Figure 10. 96-hour forecast error vs 00-hour error. Scatter-plot of the 96-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

4.2.8 Forecast Error vs Initial Error Stratified by Intensity

To further explore the correlation between hourly forecast error and 00-hour error, all of the forecasts analyzed in the preceding section (Figures 5 through 11) were stratified by intensity. The intensity used in the stratification was the intensity recorded for the storm at the time the model was initialized not the storm intensity forecast for the valid time. These intensities were separated into three storm intensity categories: tropical depression, tropical storm, and typhoon. Tropical depressions include cyclones with a maximum one-minute sustained wind speed less than or equal to 33 knots. Tropical storms include cyclones with a maximum

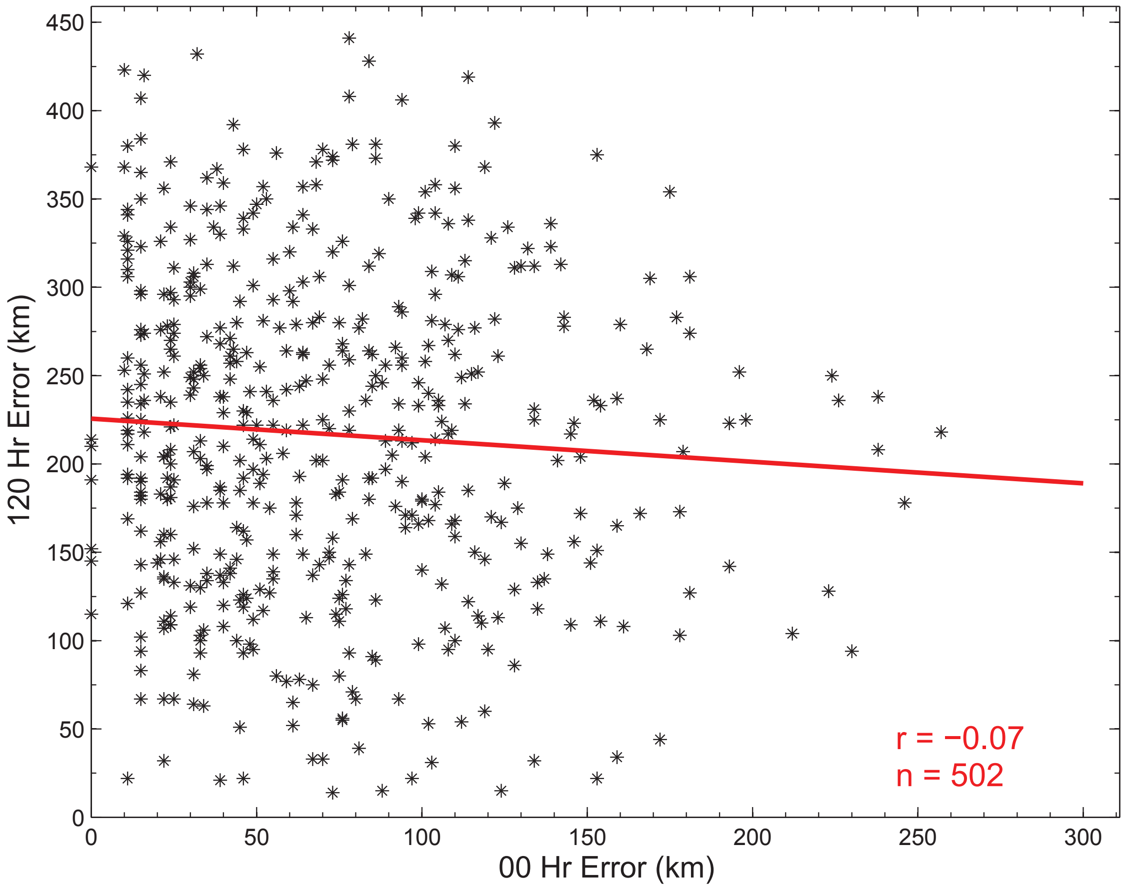

Figure 11. 120-hour forecast error vs 00-hour error. Scatter-plot of the 120-hour positional forecast error vs 00-hour forecast error. Error is defined as the distance between the GFS model derived vortex center and the JTWC best track position.

one-minute sustained wind speed of 34 knots or greater but less than 64 knots. And finally, typhoons include cyclones with a maximum one-minute sustained wind speed of 64 knots or greater. No distinction was made between typhoon and super typhoon strength storms because the sample size of the super typhoon category was very low.

As shown in Table 1 the correlations between the 12-hour forecast errors and the the corresponding 00-hour forecast errors are all significantly positive (≥ 0.32) for all three tropical cyclone categories. For the typhoon category, in particular, this positive correlation quickly decreases, becoming negative at the 48-hour point, while the other two categories show a slower degradation in correlation. For each category, there is no significant correlation between 96- and 120-hour forecast error

Table 1. Table of correlation coefficients between the initial (00-hour) positional forecast error and the subsequent hourly positional forecast error. The error used in these calculations is defined as the distance between the storm position as indicated by JTWC's best track data file and the model identified vortex in the GFS global weather model.

Hourly Forecast Error vs 00-hour Error Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
Tropical Depression	12	455	0.40
	24	414	0.17
	36	389	0.18
	48	368	0.12
	72	330	0.08
	96	287	0.02
	120	231	-0.02
Tropical Storm	12	502	0.32
	24	454	0.15
	36	405	0.10
	48	363	0.06
	72	275	-0.10
	96	200	-0.17
	120	132	-0.13
Typhoon	12	375	0.37
	24	365	0.17
	36	342	0.06
	48	311	-0.09
	72	250	-0.13
	96	193	-0.12
	120	139	-0.07

and 00-hour error.

The negative correlations between initial (00-hour) forecast error and the 96 and 120-hour forecast error shown in Figures 10 and 11 prompted closer inspection. These data imply that less accurate initial (00-hour) positions often accompanied more accurate 96 and 120-hour forecasts and vice versa (even though the relationship was minimal). Typically speaking, as a storm is sheared apart and decays, the tracking the vortex of the storm becomes more difficult. This tracking difficulty is also often encountered during the early stages of storm development, when the storm's structure can be quite disorganized. The probability of a typhoon strength storm maintaining typhoon intensity for 120 hours (5 days) is not high, but the likelihood of a developing weak depression or tropical storm strength system intensifying into a robust, symmetrical tropical cyclone is much higher. It is possible that, if the initial position is accurate, the storm is more likely to be near peak intensity and the position accuracy of the forecast will degrade over the next 96 to 120 hours as the storm decays. Conversely, if the initial location of a storm vortex is poorly defined due to its weak intensity then, in all likelihood, it will gain intensity, increasing accuracy in the vortex forecast in 96 to 120 hours. This paradigm would seem to explain the negative correlations seen in Figures 10 and 11 as well as in Table 1 between 00-hour error and 96/120-hour error.

4.3 Along/Cross-Track Error vs Initial Error

Next, the forecast positional error was decomposed into an along-track component and a cross-track component. The along-track component of the positional error can be thought of as error in gaging the speed of the storm within the model. This means the model propagated the storm either too quickly or not quickly enough. Similarly, the cross-track component of the positional error is associated with errors in the direction of movement for the storm within the model. Combining the two error components, along-track and cross-track, by taking the root of the sum of the squares yields the total error analyzed in the previous section. Comparing each component of the forecast positional error against the 00-hour forecast error as in the previous section revealed no correlation.

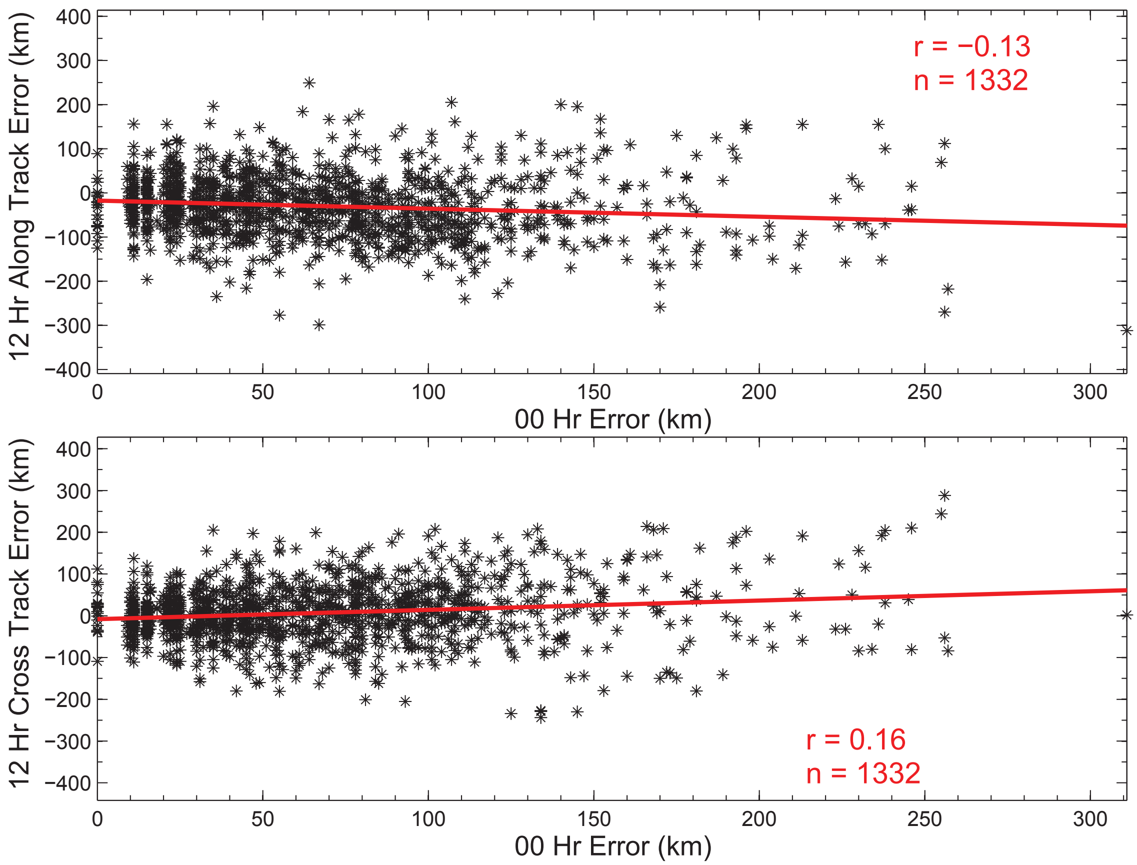

Figure 12. 12-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.3.1 12-hour Along/Cross-Track Error

Figure 12 depicts the along-track component of GFS forecast position error and the cross-track component versus the 00-hour GFS total positional error. The along-track error showed a negative correlation of -0.13 for a sample size of 1332 forecasts while the cross-track error showed a positive correlation of 0.16 from the same sample size. Such small correlations indicate that the amount of total position error present in the 00-hour forecast has little influence on the amount of along-track or cross-track error at the 12-hour forecast point.

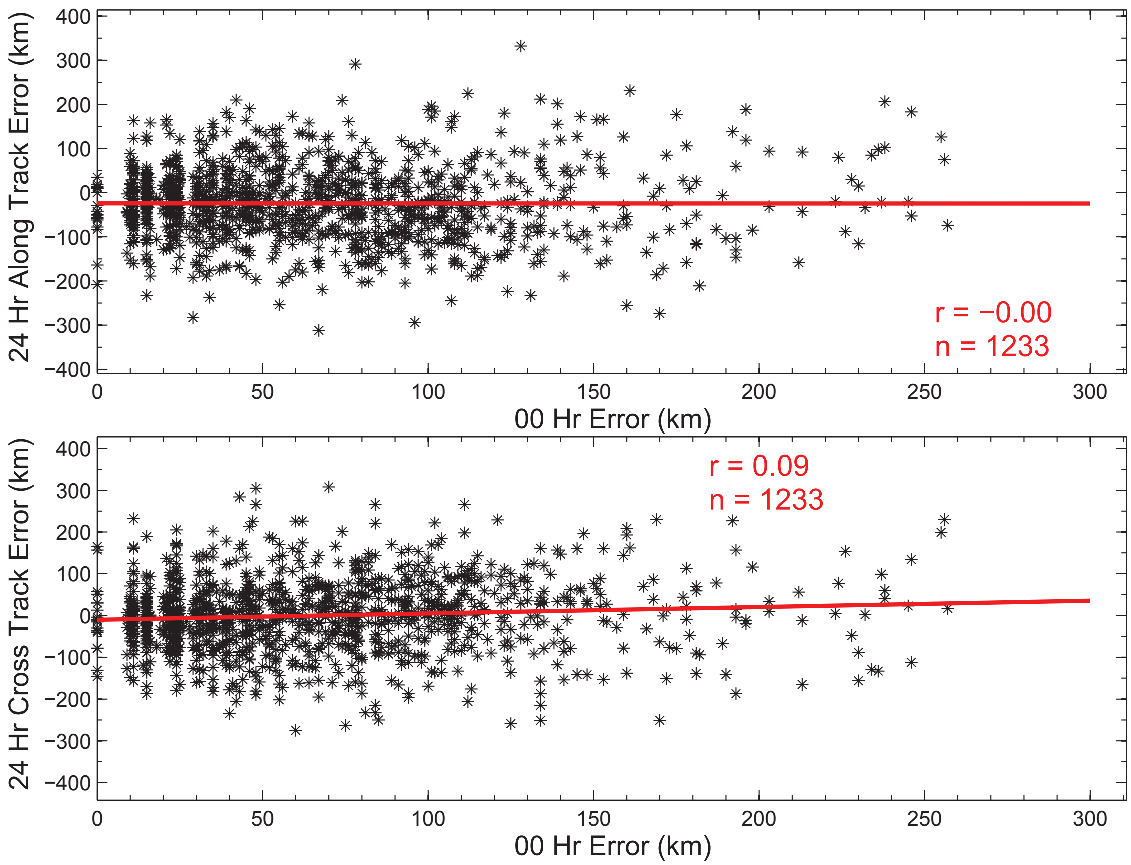

Figure 13. 24-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.3.2 24-hour Along/Cross-Track Error

The 24-hour along-track and cross-track components also showed no correlation with 00-hour error. The along-track component of the 24-hour positional error had a correlation coefficient of 0.00 while the cross-track error component had a correlation coefficient of 0.09 (Figure 13), both for a sample size of 1233 24-hour forecasts. Such small correlations indicate that the responses seen in along-track and cross-track components of the total error cannot be attributed to the positional accuracy of the 00-hour forecast.

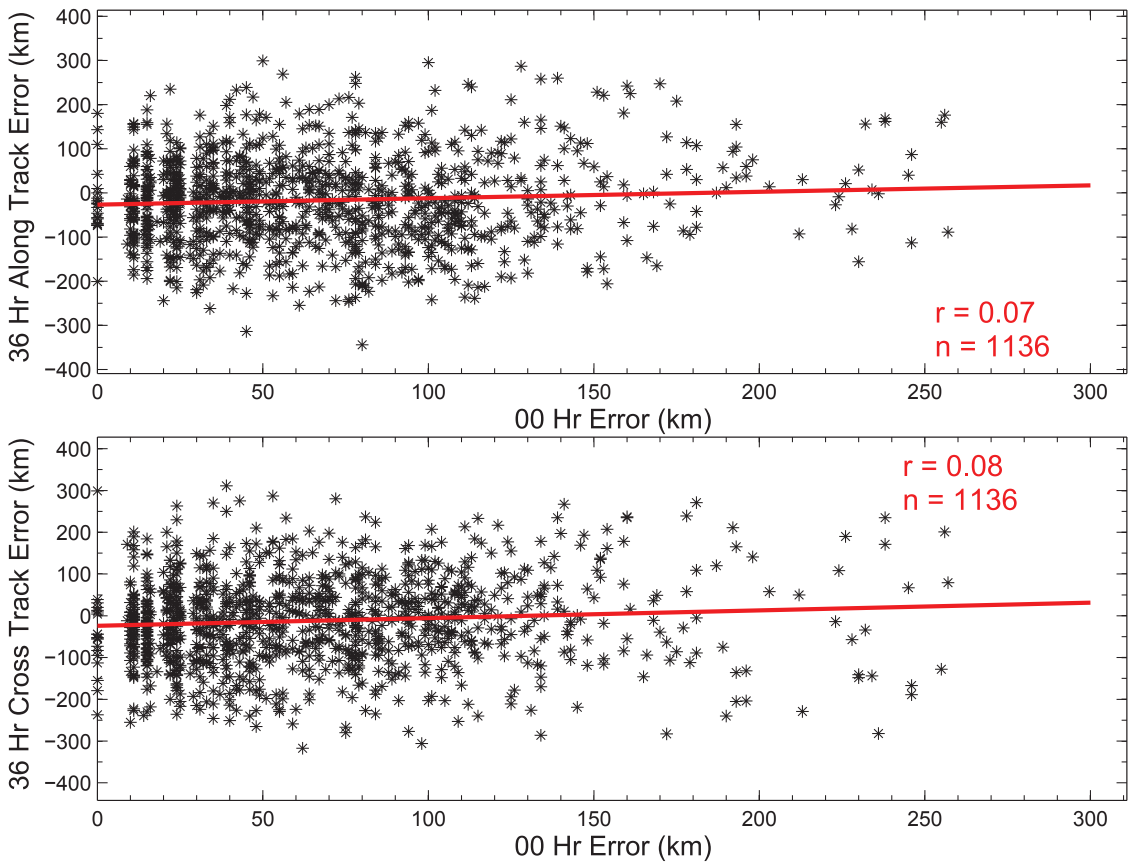

Figure 14. 36-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.3.3 36-hour Along/Cross-Track Error

Both the along-track and the cross-track errors at the 36-hour forecast point show no effective correlation with the corresponding 00-hour error (Figure 14). The along-track error/00-hour error correlation coefficient was 0.07 correlation coefficient, while the cross-track error/00-hour error correlation coefficient was 0.08, both base on 1136 cases.

4.3.4 48-hour Along/Cross-Track Error

At the 48-hour forecast point, the sample size continued to decrease while there continued to be no correlation between either the along-track component or

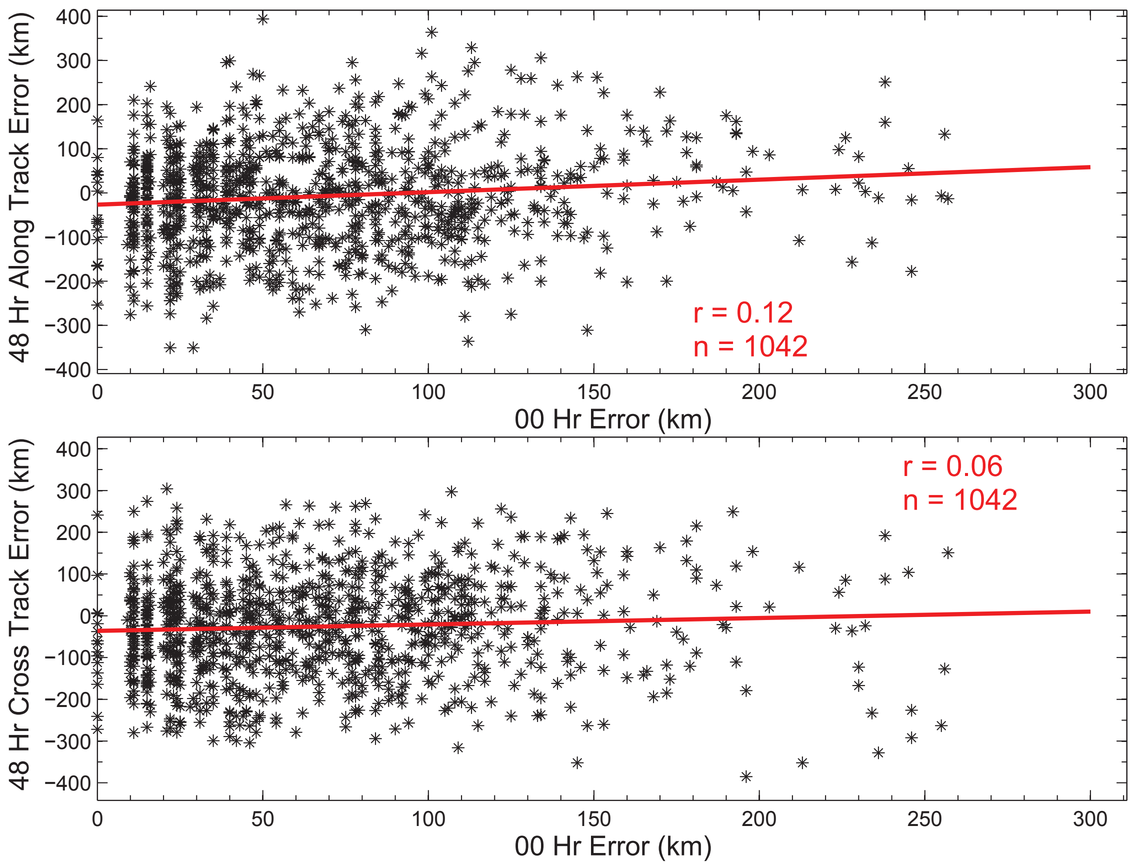

Figure 15. 48-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

cross-track component of the total error with the corresponding 00-hour error (Figure 15). The 48-hour along-track error and 00-hour error correlation coefficient was 0.12 while the cross-track error and 00-hour error correlation coefficient was 0.06, both based on 1042 48-hour forecasts.

4.3.5 72-hour Along/Cross-Track Error

Figure 16 shows that no effective correlation existed between either the along-track error component and 00-hour error or the cross-track error component and 00-hour error at the 72-hour forecast point. The correlation coefficients were 0.05 and 0.03 for the along-track error and cross-track error, respectively. The sample size for the 72-hour along and cross-track analysis was 855 forecasts.

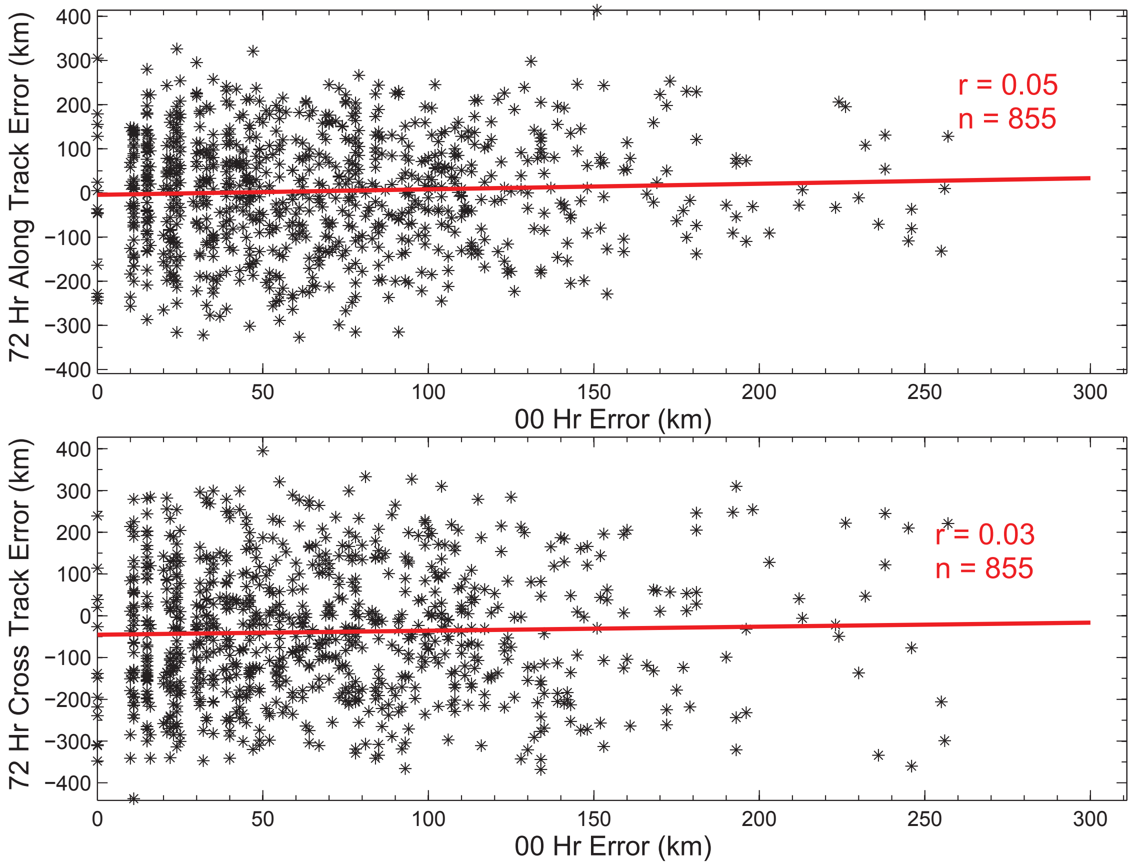

Figure 16. 72-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.3.6 96-hour Along/Cross-Track Error

Again, the 96-hour analysis of along-track error and cross-track error at 96 hours showed no correlation between either component of total error and the corresponding 00-hour error (Figure 17). The along-track error and 00-hour error correlation was actually slightly negative at 0.08 while the cross-track error and 00-hour error correlation coefficient is positive at 0.06. 680 96-hour forecasts were analyzed.

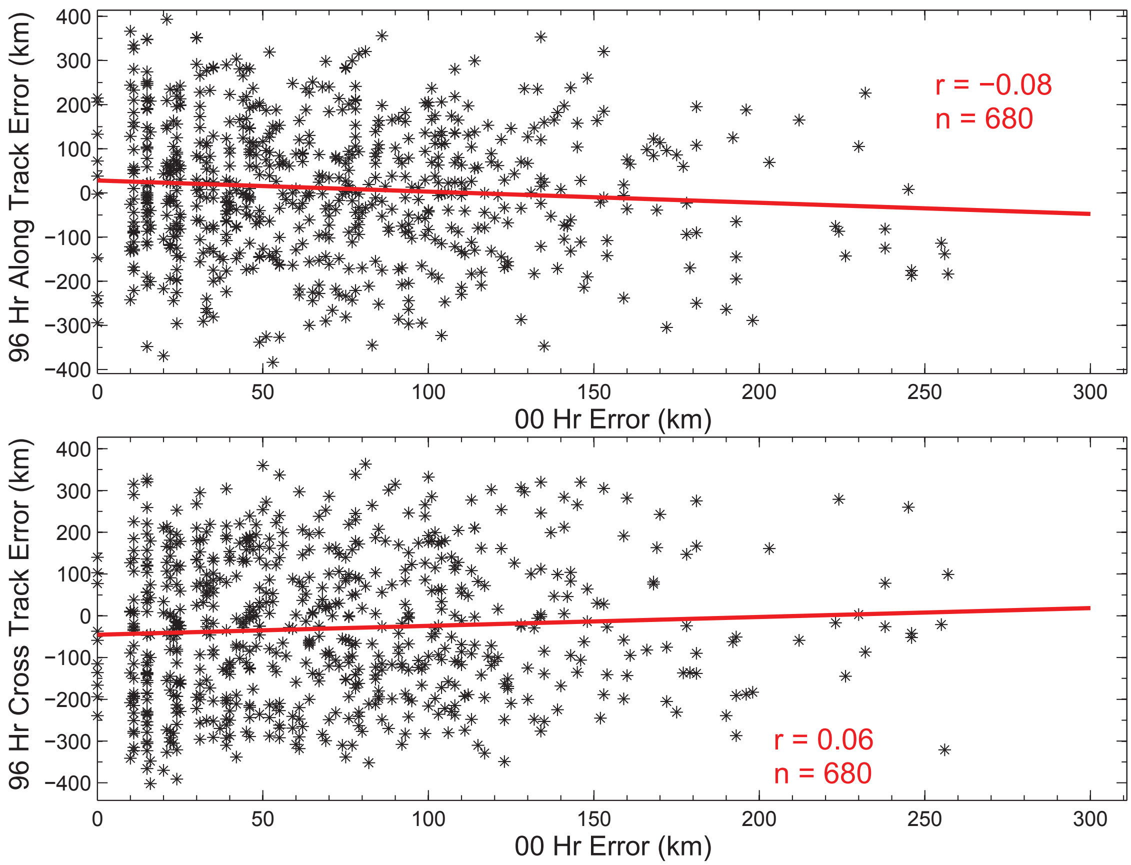

Figure 17. 96-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.3.7 120-hour Along/Cross-Track Error

The along-track error and cross-track error at the 120-hour point also did not correlate with the 00-hour forecast (Figure 18). The along-track component of error and 00-hour forecast error showed a negative correlation coefficient of 0.11 while the cross-track error analysis showed a positive correlation with 00-hour forecast error of 0.03. 502 120-hour forecasts were analyzed.

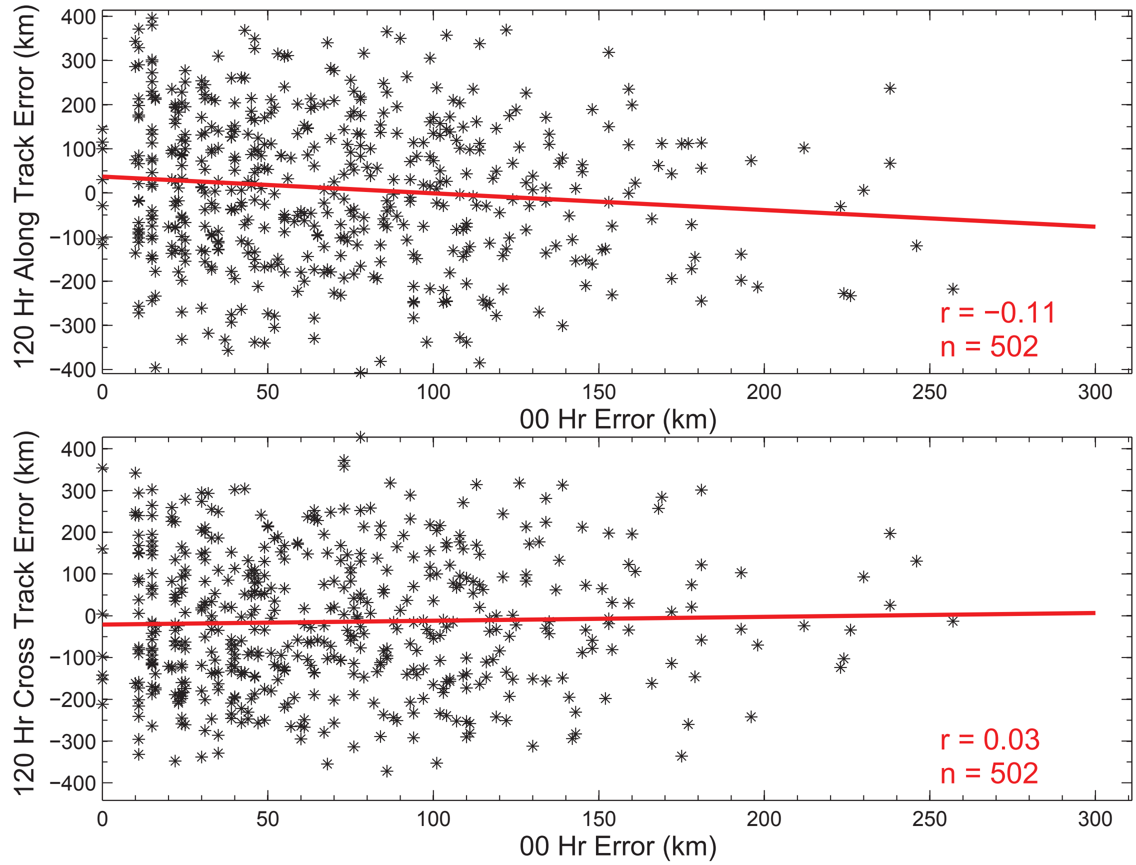

Figure 18. 120-hour along/cross-track forecast error vs 00-hour error. Also shown are the associated correlation coefficients and sample sizes.

4.4 GFS Model Parameter Spread vs Forecast Error

To further investigate the relationship between analysis and forecast errors, the spread among the model parameters used in locating the vortex within the GFS model was compared to the total model forecast error at each forecast hour out to 120 hours. The spread indicates how organized the modeled vortex was at a particular forecast hour. In comparing the model parameter spread to the positional forecast error, forecast hours 00 through 24 showed a reasonably strong positive correlation (compared to correlations previously looked at in this chapter) while forecast hours 36 through 120 showed effectively no correlation.

Similar to the figures in sections 4.2 and 4.3, Figures 19 through 26 also depict data from all the GFS model runs from the 2011 to 2012 tropical cyclone seasons analyzed against JTWC best track data. Figures 19 through 26 compare the model parameter spread and positional forecast error valid for the same forecast hour, rather than comparing forecast error with the initial (00-hour) forecast error. If a strong correlation were to exist between parameter spread and forecast error, then forecasters could possibly infer forecast positional error in the model by assessing the level of agreement among the seven model parameters used in locating the vortex. However the correlations found are not strong enough to merit implementing such a method. Each plot again shows a best fit line in red as well as the forecast sample size and correlation coefficient.

4.4.1 00-hour Parameter Spread vs Position Error

The 00-hour plot of model parameter spread versus positional error shows a strong correlation, the strongest observed thus far in this project. The correlation coefficient is 0.41 from a sample size of 1391 forecasts (Figure 19). This positive correlation shows that, overall, initial forecast position error is somewhat correlated with the spread in the seven model parameters used in locating the vortex. If the spread among the model parameters is small (i.e. the storm is well organized and the model parameters seem to agree on the vortex location), then analysis positional error tends also be small.

4.4.2 12-hour Parameter Spread vs Position Error

The 12-hour analysis of model parameter spread versus positional error still shows a positive correlation of 0.26. The sample size for this subset of data is 1347 (Figure 20). Similar to the correlation shown in the 00-hour model spread plot (Figure 19), the 12-hour forecast position error is also reasonably correlated with

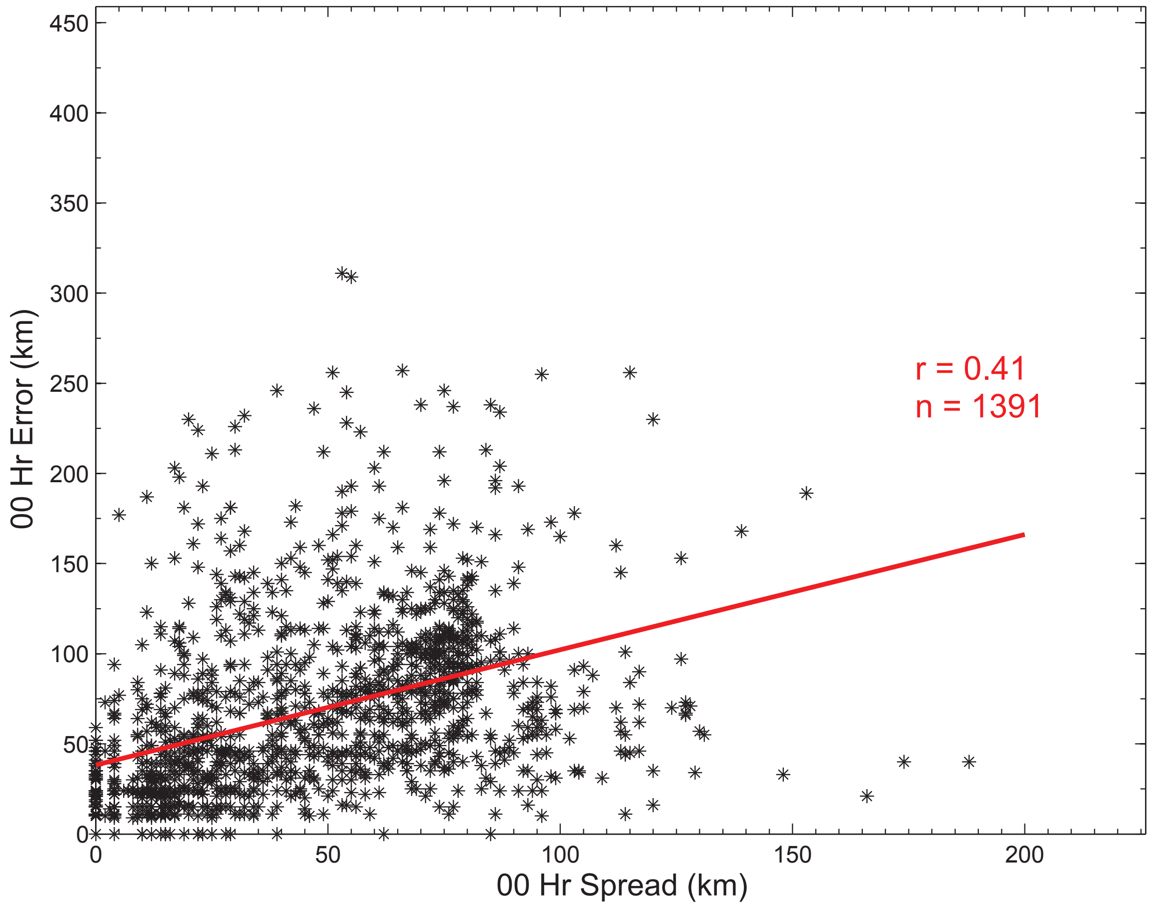

Figure 19. 00-hour error vs 00-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

the model vortex parameter spread. It is worth noting the apparent preferential values of spread which appear in Figure 20 and the remaining figures in this section, between approximately 75-80 km and at again at around 20 km.

4.4.3 24-hour Parameter Spread vs Positional Error

At 24-hours, the correlation between the forecast positional error and the model parameter spread is 0.18 for a sample size of 1252 forecasts (Figure 21). This correlation is on par with the majority of the correlations seen in the previous sections of this chapter, indicating the possibility of a very small influence of

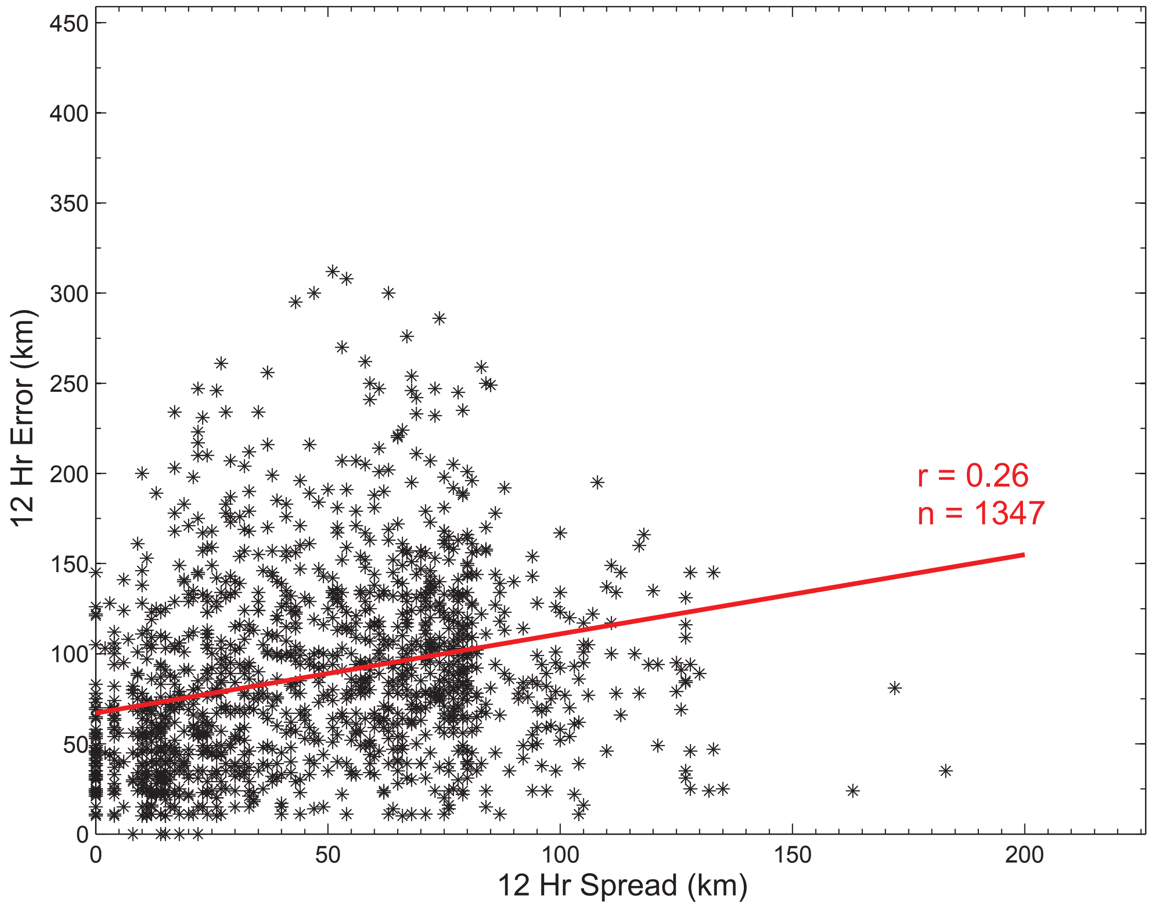

Figure 20. 12-hour error vs 12-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

parameter spread on forecast error.

In this plot, and for other forecast hours, there was a significant number of cases in which the model spread is exactly zero. In theses cases, each of the parameters used in locating the vortex agreed on the same grid point as the center of the vortex. In most cases, though, even with agreement among all seven parameters, the forecast position was still different than the true vortex position reported in the JTWC post-analysis.

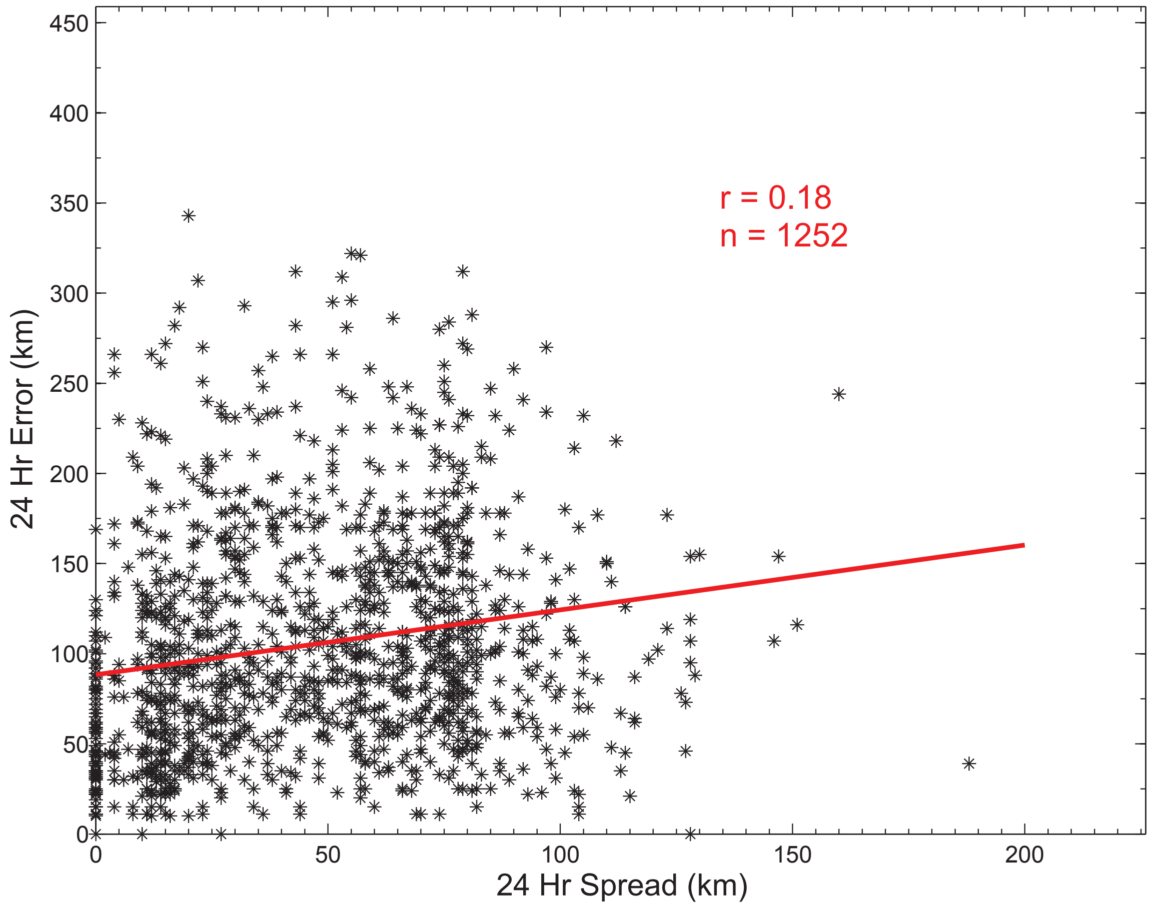

Figure 21. 24-hour error vs 24-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

4.4.4 36-hour Parameter Spread vs Position Error

The 36-hour analysis of model parameter spread versus forecast positional error had a 0.09 correlation coefficient with a sample size of 1157 forecasts (Figure 22). By the 36-hour forecast, the correlation is trending toward neutral, but still has a slight positive correlation exists.

4.4.5 48-hour Parameter Spread vs Position Error

The correlation coefficient for the 48-hour forecast position error versus parameter spread plot is 0.03, calculated from a sample size of 1064 forecasts

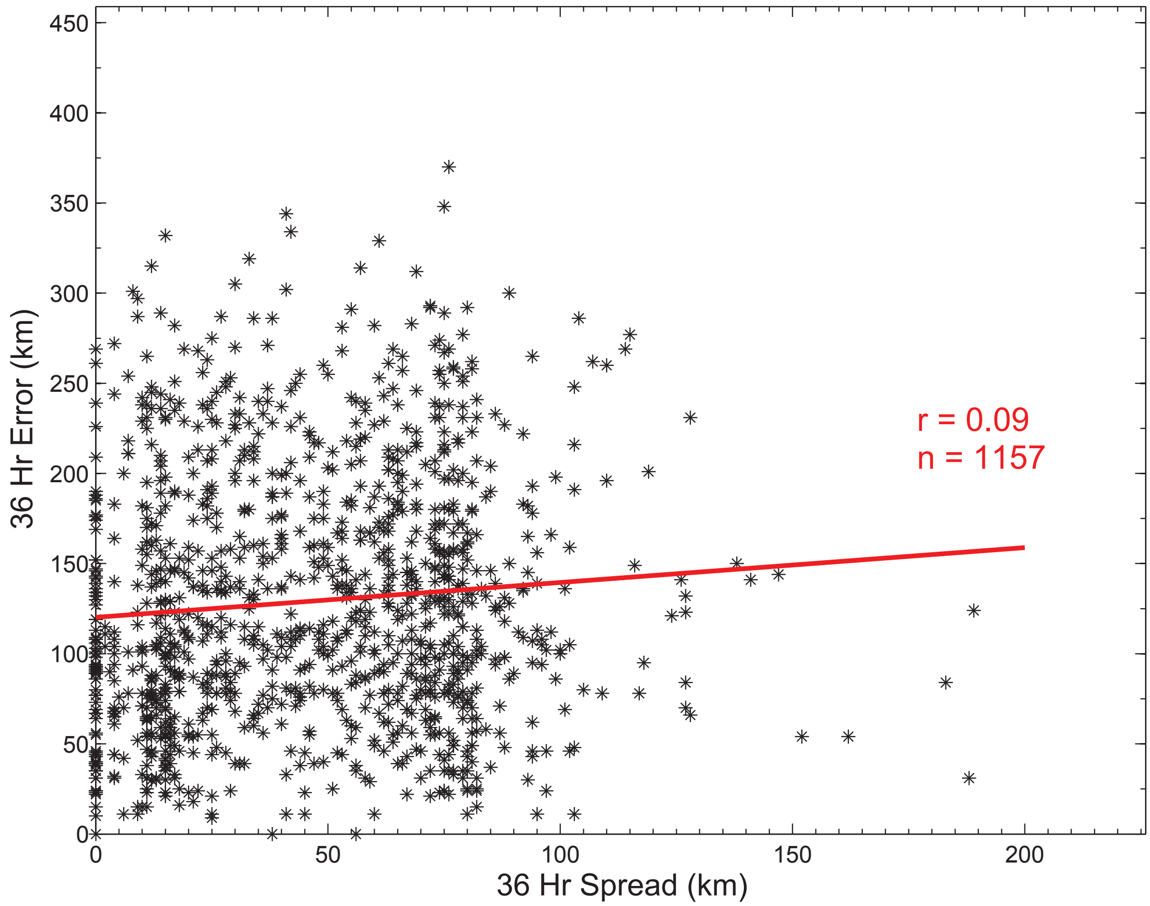

Figure 22. 36-hour error vs 36-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

(Figure 23). The small correlation indicates that no real correlation exists between the model parameter spread and the corresponding 48-hour positional forecast error. Figure 23, shows overall forecast errors trending upwards, but the two preferential spread values, at 20 km and 75-80 km, still exist.

4.4.6 72-hour Parameter Spread vs Position Error

At 72-hours, the correlation between the forecast position error and model parameter spread (Figure 24) was 0.05, from a sample size of 878 forecasts. Although the actual value of the correlation coefficient is slightly larger than the

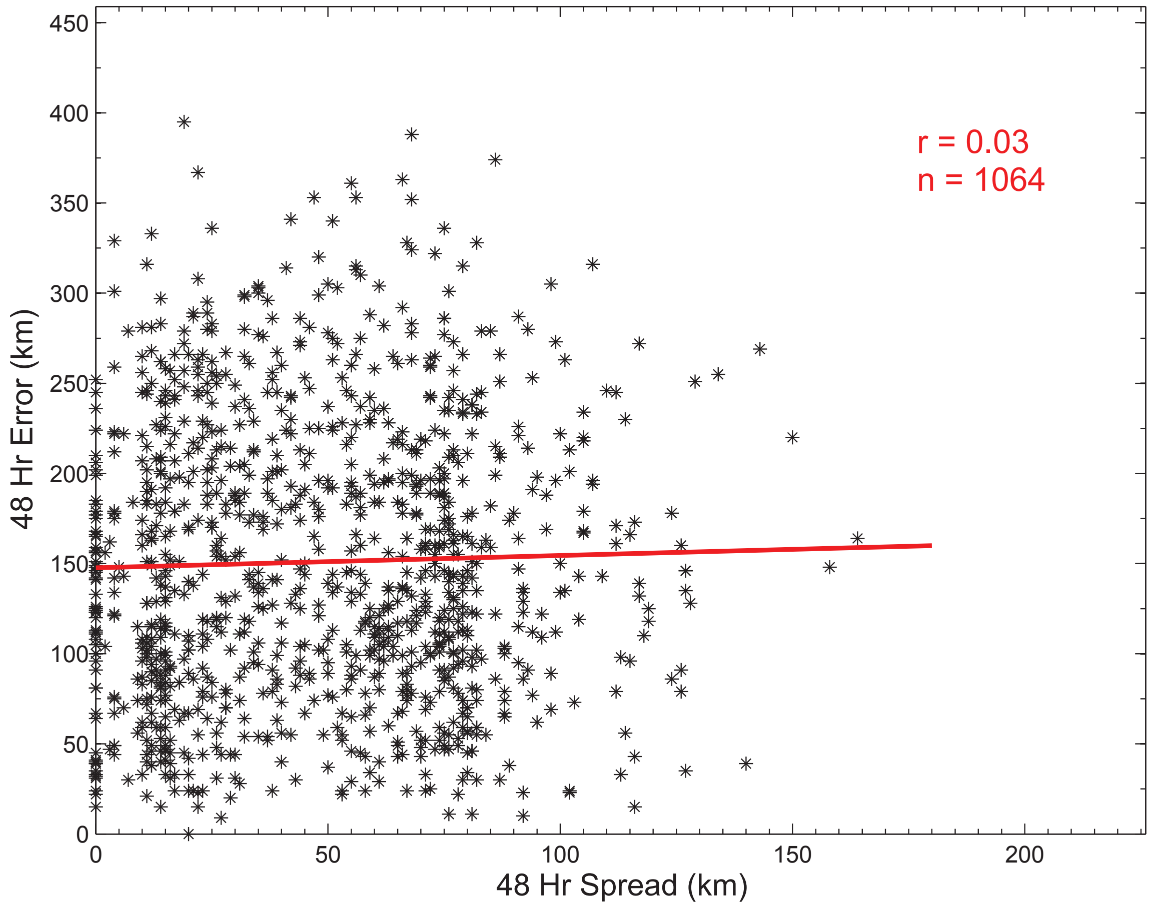

Figure 23. 48-hour error vs 48-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

48-hour forecast analysis, both correlation coefficients are effectively zero.

4.4.7 96-hour Parameter Spread vs Position Error

By 96 hours, a negative correlation between positional forecast error and model parameter spread is evident (Figure 25). From a sample size of 702 forecasts, the correlation coefficient was -0.03, indicating a weak inverse relationship between 96-hour parameter spread and positional error. A negative correlation here means a smaller model spread actually indicates a larger positional error in the 96-hour forecast, however such a small correlation is not significantly different than zero.

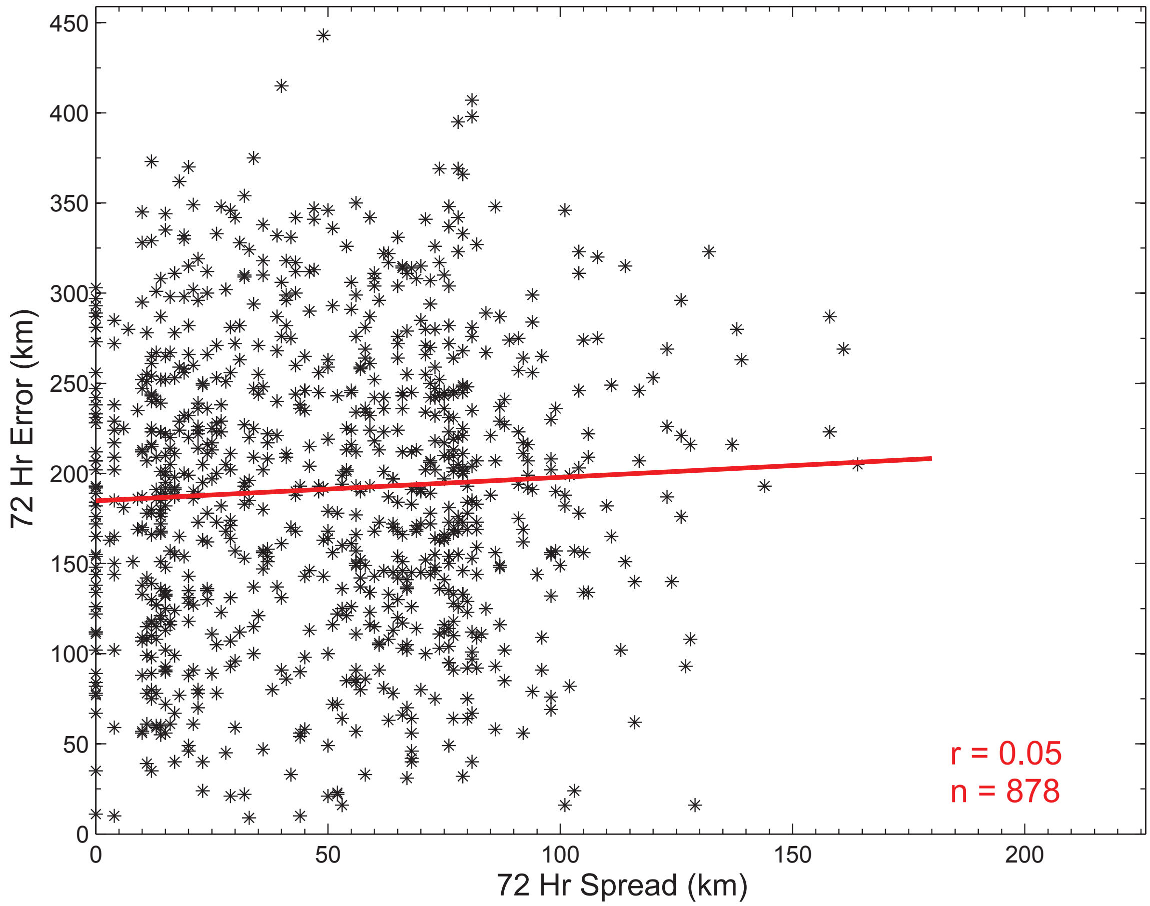

Figure 24. 72-hour error vs 72-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

4.4.8 120-hour Parameter Spread vs Positional Error

The five day forecast data in Figure 26 again shows effectively no correlation between forecast error and model parameter spread. The correlation coefficient was 0.01, calculated from a sample size of 522 120-hour forecasts.

4.4.9 GFS Model Parameter Spread vs Forecast Error Stratified by Intensity

As with the forecast-hour versus 00-hour position error relationship, the forecast position error versus parameter spread relationship was analyzed for each category

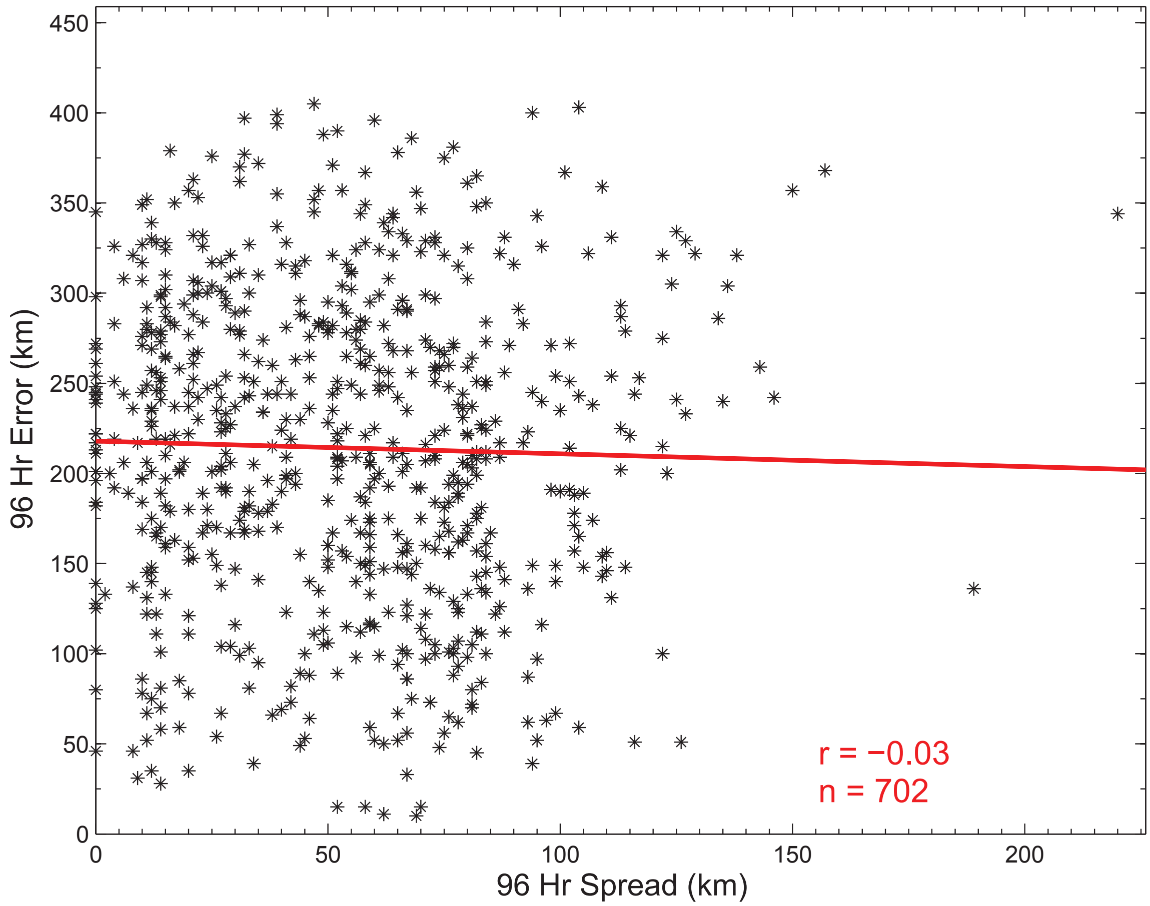

Figure 25. 96-hour error vs 96-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

of storm intensity, as reported in the best-track data, at the valid time of the forecast. These forecasts were again stratified into three storm intensity categories: tropical depression, tropical storm, and typhoon, as described in section 4.2.8. Table 2 summarizes the correlations calculated through this analysis for each storm category.

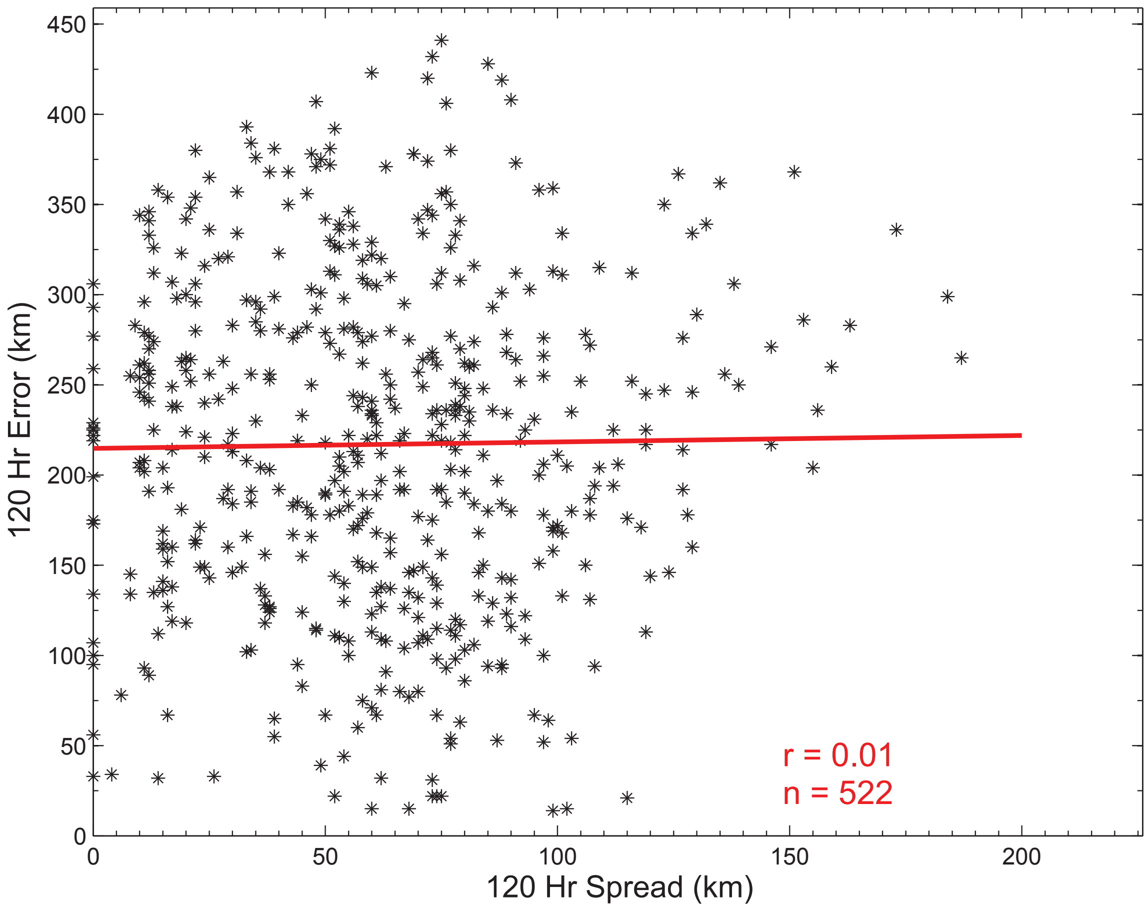

Figure 26. 120-hour error vs 120-hour model vortex tracker parameter spread. Error is defined as the distance between the model derived vortex center and the JTWC best track position.

Table 2. Correlations between hourly model parameter spread and hourly forecast error stratified by intensity. The error used in these calculations is defined as the distance between the storm position as indicated by JTWC's best track data file and the model identified vortex position in the GFS global weather model.

Hourly Forecast Error vs Hourly Parameter Spread Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
Tropical Depression	00	486	0.24
	12	441	0.12
	24	344	0.00
	36	267	-0.02
	48	219	-0.10
	72	153	-0.02
	96	112	0.16
	120	81	0.02
Tropical Storm	00	529	0.49
	12	526	0.24
	24	527	0.18
	36	507	0.07
	48	464	0.04
	72	362	-0.03
	96	267	-0.13
	120	198	-0.03
Typhoon	00	376	0.68
	12	380	0.49
	24	381	0.27
	36	383	0.13
	48	381	0.03
	72	363	0.14
	96	323	-0.03
	120	243	-0.01

As evident in Table 2, the forecast hours 00 and 12 for each storm category show stronger correlations than the vast majority of subsequent forecast hours. The typhoon category exhibits the strongest correlation, 0.68, at forecast hour 00. The correlation decays somewhat at the 12-hour forecast point and continues to decrease to 0.27 by forecast hour 24. This implies that for typhoon-strength storms, the forecast error out to 24 hours can be anticipated by evaluating the spread among the seven model parameters used to locate the model vortex. However, the parameter spread still explains only a small fraction of the error variance at any forecast hour for any of the tropical cyclone categories.

4.5 GFS Model Parameter Spread vs Along/Cross-Track Error

This section focuses on the relationship between hourly model vortex tracker parameter spread and hourly along and cross-track error. The data is summarized in two tables, one listing the parameter spread versus along-track error relationship, and another listing the parameter spread versus cross-track error relationship. This analysis was also stratified by storm intensity categories, and the results are also displayed in the same two tables.

4.5.1 Hourly Parameter Spread vs Along-Track Error

Table 3 contains correlation coefficients and sample sizes for each forecast hour. For all forecast hours and all intensity categories, the calculated correlation coefficients were very small, with the largest correlation coefficient value of 0.18 associated with the 12-hour parameter spread and along-track error in the typhoon category. The correlation coefficients shown in Table 3 indicate that nearly no correlation exists between along-track error and parameter spread for any forecast hour at any storm intensity.

4.5.2 Hourly Parameter Spread vs Cross-Track Error

Table 4 contains correlation coefficients and sample sizes for the hourly parameter spread and hourly cross-track error analysis. The majority of the correlation coefficients in this table are negative, with a few of the values exceeding -0.20 and one reaching -0.31. However, as with the values listed in Table 3, these correlation coefficients are not large enough to prove a strong link between the hourly parameter spread and corresponding cross-track error.

Table 3. Correlations between hourly model parameter spread and hourly along-track error.

Hourly Along-Track Error vs Hourly Parameter Spread Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
All Storms	00	1392	0.08
	12	1348	0.10
	24	1253	0.07
	36	1158	0.04
	48	1065	0.04
	72	879	-0.02
	96	703	0.08
	120	523	0.03
Tropical Depression	00	487	0.11
	12	442	0.06
	24	345	-0.05
	36	268	0.01
	48	220	-0.01
	72	154	-0.01
	96	113	0.08
	120	82	0.00
Tropical Storm	00	530	0.03
	12	527	0.05
	24	528	0.11
	36	508	0.00
	48	465	0.03
	72	363	0.06
	96	268	0.13
	120	199	0.07
Typhoon	00	377	0.13
	12	381	0.18
	24	382	0.14
	36	384	0.09
	48	382	0.10
	72	364	-0.03
	96	324	0.03
	120	244	0.02

Table 4. Correlations between hourly model parameter spread and hourly cross-track error.

Hourly Cross-Track Error vs Hourly Parameter Spread Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
All Storms	00	1392	-0.19
	12	1348	-0.11
	24	1253	-0.08
	36	1158	-0.08
	48	1065	0.02
	72	879	-0.03
	96	703	-0.17
	120	523	-0.08
Tropical Depression	00	487	-0.10
	12	442	-0.06
	24	345	-0.02
	36	268	-0.16
	48	220	-0.02
	72	154	-0.16
	96	113	-0.07
	120	82	-0.06
Tropical Storm	00	530	-0.23
	12	527	-0.09
	24	528	-0.05
	36	508	-0.07
	48	465	0.07
	72	363	0.05
	96	268	-0.07
	120	199	-0.02
Typhoon	00	377	-0.31
	12	381	-0.23
	24	382	-0.12
	36	384	0.01
	48	382	0.02
	72	364	-0.10
	96	324	-0.21
	120	244	-0.13

4.6 Hourly Forecast Error vs 00-Hour MSLP

This section analyzes the relationship between hourly forecast error and 00-hour MSLP. MSLP is often used to quantify storm intensity; the lower the central pressure the more intense the storm. Typically more intense storms are easier to locate due to a more well-defined vortex so one might assume that stronger storms at hour 00 would produce more accurate position forecasts. Table 5 contains correlation coefficients and sample sizes between 00-hour MSLP and forecast hour GFS position error for all storm intensities, as well as individual intensity categories.

Table 5, shows that the majority of the calculated correlation coefficients are negative. This indicates that weaker storms produce larger position forecast errors, as we would expect. The 120-hour forecast in the *All Storms* category of Table 5 shows a positive correlation of 0.07, indicating that weaker storms produce better 120-hour positional forecasts. The typhoon category comprises about 1/3 of all the 120-hour forecasts, and with a correlation coefficient of 0.22, bears the most weight in the 0.07 120-hour correlation coefficient. Bearing in mind the MSLP along the x-axis is from the model initialization time (00-hour) and not the model verification time (120-hours), this positive correlation indicates the weaker the storm initially (time 00), the better the 120-hour forecast. Likewise, the stronger the storm initially, the worse the 120-hour forecast (in plotting the data for this section, the x-axis was reversed to show decreasing MSLP values (increasing storm intensity) moving toward the right). This result follows the explanation from the end of section 4.2, where it was mentioned that for longer forecasts (96 and 120-hours) storms often strengthen or weaken significantly from their current intensity. For intensifying storms, the vortex location is more ambiguous initially and more well-defined once the storm strengthens.

Table 5. Correlations between hourly forecast error and 00-hour MSLP indicated in the JTWC best track data.

Hourly Forecast Error vs 00-Hour MSLP Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
All Storms	12	1332	-0.28
	24	1233	-0.26
	36	1136	-0.26
	48	1042	-0.24
	72	855	-0.14
	96	680	0.00
	120	502	0.07
Tropical Depression	12	455	-0.16
	24	414	-0.16
	36	389	-0.20
	48	368	-0.18
	72	330	-0.09
	96	287	0.07
	120	231	0.07
Tropical Storm	12	502	-0.03
	24	454	0.03
	36	405	0.02
	48	363	-0.03
	72	275	-0.06
	96	200	-0.02
	120	132	-0.19
Typhoon	12	375	0.06
	24	365	-0.10
	36	342	-0.12
	48	311	-0.13
	72	250	-0.12
	96	193	0.15
	120	139	0.22

4.7 Hourly Forecast Error vs 00-Hour Maximum Sustained Wind

Next, the maximum one-minute sustained wind speed was used as the primary indicator of storm intensity. We would expect similar trends between storm intensity quantified by wind speed and hourly forecast error as indicated in the MSLP analysis. Table 6 contains the correlation coefficients and sample sizes between hourly forecast error and corresponding 00-hour maximum one-minute sustained wind speed. The correlation coefficients are very similar to the values in Table 5. This is not surprising, as maximum sustained wind speed and MSLP are closely related to each other.

Table 6. Correlations between hourly forecast error and 00-hour wind speed indicated in the JTWC best track data.

Hourly Forecast Error vs 00-Hour Max Wind Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
All Storms	12	1332	-0.28
	24	1233	-0.26
	36	1136	-0.26
	48	1042	-0.24
	72	855	-0.14
	96	680	0.00
	120	502	0.07
Tropical Depression	12	455	-0.16
	24	414	-0.15
	36	389	-0.19
	48	368	-0.16
	72	330	-0.07
	96	287	0.05
	120	231	0.07
Tropical Storm	12	502	-0.03
	24	525	0.03
	36	503	0.03
	48	456	-0.02
	72	351	-0.06
	96	258	-0.02
	120	193	-0.19
Typhoon	12	375	0.06
	24	365	-0.10
	36	342	-0.12
	48	311	-0.13
	72	250	-0.12
	96	193	0.15
	120	139	0.22

4.8 Hourly Forecast Error vs 00-hour Latitude

This section investigates whether hourly forecast error is related to the initialized latitude of the storm. Storms normally develop at lower-latitudes and as they intensify, they typically move poleward. During this poleward transition, storms may transition from a tropical environment dominated by easterly synoptic flow to westerly synoptic flow in the mid-latitudes. Accompanying this change in the synoptic pattern comes a change in the the direction of movement of most tropical cyclones. Generally, storms at lower latitudes move west or northwestward and as the synoptic pattern changes to the mid-latitude westerlies, the storms re-curve to a more northward or even northeastward track. The exact point at which the storms begin o change direction is difficult to forecast and can be a source of positional error. Table 7 contains calculated correlation coefficients and sample sizes from the analysis of hourly forecast error and 00-hour storm latitude. These correlations are still very low, indicating a very weak relationship, if any, between the initial latitude of the storm and the GFS forecast positional error. This shows that the GFS model does not appear to show a bias in positional error among any of the forecast hours for any of tropical cyclone intensities for storms in the wester North Pacific basin.

Table 7. Correlations between hourly forecast error and 00-hour latitude indicated in the JTWC best track data.

Hourly Forecast Error vs 00-Hour Latitude Correlations			
Category	**Forecast Hour**	**Sample Size**	**Correlation**
All Storms	12	1332	-0.10
	24	1233	0.02
	36	1136	0.04
	48	1042	0.07
	72	855	0.03
	96	680	0.07
	120	502	-0.02
Tropical Depression	12	455	-0.08
	24	414	0.07
	36	389	0.02
	48	368	0.03
	72	330	-0.03
	96	287	0.05
	120	231	-0.10
Tropical Storm	12	502	0.11
	24	454	0.18
	36	405	0.13
	48	363	0.10
	72	275	-0.03
	96	200	0.03
	120	132	0.03
Typhoon	12	375	-0.14
	24	365	0.05
	36	342	0.14
	48	311	0.27
	72	250	0.25
	96	193	0.17
	120	139	0.08

Table 8. Correlations between hourly error and initial position error for 2013. The error in these calculations is defined as the distance between the storm position as indicated by JTWC's warning bulletins and the model identified vortex in the GFS global weather model.

2013: Hourly Forecast Error vs 00-hour Error Correlations		
Forecast Hour	**Sample Size**	**Correlation**
12	669	0.58
24	624	0.30
36	570	0.16
48	522	0.06
72	420	0.10
96	330	0.10
120	240	-0.02

4.9 2013 Tropical Cyclone Season Data Analysis

Data from the 2013 tropical cyclone season were initially analyzed separately due to the application of JTWC tropical cyclone warning bulletin locations rather than post-analyzed best track data. This methodological change was required because the 2013 best track data was not yet available. As discussed earlier, the best track data is typically more accurate than the warning bulletin analysis positions because the analysts producing the best-track analysis have more data and time available to adjust the post-analysis best-tracks. The same analyses were performed on the 2013 dataset as were performed on the 2011-2012 dataset, and similar results were obtained. Table 8 contains correlation coefficeints for GFS forecast-hour positional error versus 00-hour positional error for the 2013 dataset. These correlations are similar to the values in Table 4.2 for 2011-2012.

V. Conclusions

5.1 Summary

The objective of this study was to investigate the effect of initial (00-hour) tropical cyclone positional errors on the GFS 96 and 120-hour forecast tropical cyclone positional errors. To achieve this task, GFS model forecasts for 87 western North Pacific storms from the 2011 (27), 2012 (27), and 2013 (33) storm seasons were analyzed. Positional comparisons were calculated between JTWC post-analyzed best track storm positions and the vortex positions identified in the GFS model for each forecast hour. Scatter-plots showing best fit lines and correlation coefficients between several variables, including hourly positional forecast error and parameter spread, were created to show whether initial (00-hour) positional error could be an indicator of positional forecast error in 96 and 120-hour forecasts or if other parameters could be used by forecasters to predict model forecast positional errors or systematic biases four and five days in advance.

The storm vortex was tracked within the GFS model (following a modified NCEP tracker routine) by averaging the storm position according to seven parameters (MSLP, 850mb relative vorticity, 700mb relative vorticity, 850mb geopotential height, 700mb geopotential height, 850mb wind speed, and 700mb wind speed). The distance between the two locations (vortex within the model and vortex position recorded in the JTWC best track) was recorded as the position error. The spread among the model vortex tracking parameters was also recorded. This analysis was conducted for all forecast hours, 00 through 120, for all storms analyzed by JTWC from 2011 through 2013.

For the 87 storms comprising this study, a total of 1011 96-hour and 743 120-hour forecasts, with accompanying 00-hour model analyses, were compared.

Table 9 contains correlation coefficients and sample sizes for the 00-hour versus forecast hour position error analysis for each forecast hour. The average positional error between the best-track position and the 96-hour forecast position was 208 km. The average error at 120-hours was 214 km. Correlations between the initial positional error and the 96-and 120-hour forecast positional error were 0.00 and -0.05, respectively, indicating that the initial forecast error has no effect on forecast error at 96 and 120-hours.

Table 9. Correlations between the initial (00-hour) positional forecast error and the subsequent hourly positional forecast error for 87 storms from 2011 through 2013. The error in these calculations is defined as the distance between the storm position as indicated by JTWC's best track post-analysis and the model identified vortex in the GFS global weather model.

Hourly Error vs Initial Error Correlations		
Forecast Hour	**Sample Size**	**Correlation**
12	2001	0.51
24	1857	0.27
36	1706	0.17
48	1564	0.09
72	1276	0.04
96	1011	0.00
120	743	-0.05

While these results provide no basis upon which to reliably predict 96- and 120-hour GFS forecast position error, they may still be useful to tropical cyclone forecasters. These results suggest that tropical cyclone forecasters can avoid discrediting a model's extended track forecast simply because the analysis position appears to be inaccurate. The chaotic nature of the atmosphere does not allow positional errors to grow linearly from one forecast hour to the next as one might expect. Instead, it appears that the initial position error within the GFS model is in fact uncorrelated with extended forecast position error.

5.2 Future Research/Recommendations

Future research should first incorporate JTWC's 2013 post-analyzed best track data into this analysis, in place of the warning bulletin analysis positions used for this project. Future research should also expand the dataset of analyzed storms and explore whether other numerical weather prediction models produce similar results. The Navy Global Environmental Model (NAVGEM) and the Navy's version of the Geophysical Fluid Dynamics Laboratory model (GFDN) are candidate global models in which a study similar to this GFS study could be implemented to produce comparative results. It would be useful to determine which, if any, of these three models outperform the others or if any of the models show a noticeable bias in terms of positional track error. This research could also be expanded to other tropical cyclone basins, such as the Atlantic or eastern Pacific basin, to determine if the results from the western North Pacific basin are reproduced.

One tangential item to investigate emerged during this study: the appearance of the preferential spread values in Figures 19 to 26. Knowing the causality of this phenomenon, be it a mathematical artifact of taking geographical mean within the vortex tracker or something deeper within the model physics, may lead to a more complete understanding of the potential sources of positional error at various model forecast hours.

Finally, it would be useful to accomplish a similar study focusing on tropical cyclone intensity error rather than positional error since forecasting the intensity of a storm is often more difficult than forecasting its position and the intensity of a storm can also affect how the storm interacts with its immediate environment.

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Vita

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14. ABSTRACT

Global Forecast System (GFS) western Pacific tropical cyclone track forecasts from the 2011, 2012, and 2013 seasons (87 storms) were compared to Joint Typhoon Warning Center (JTWC) tropical cyclone best track data and warning bulletins in order to determine the sensitivity of 96 and 120-hour tropical cyclone position forecasts to initial position error. A tropical cyclone vortex tracker, which uses seven different model parameters to track storm centers, was implemented to determine model forecast positions. The differences between JTWC analysis positions and the model-derived vortex positions were analyzed at each forecast hour (00, 12, 24, 36, 48, 72, 96, and 120). The relationship between the geographical spread among the model vortex-tracking parameters and forecast errors was also considered. Correlations between error at each forecast hour and the initial 00-hour error suggest that position error has no effect on forecast error at 96 and 120-hours.

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